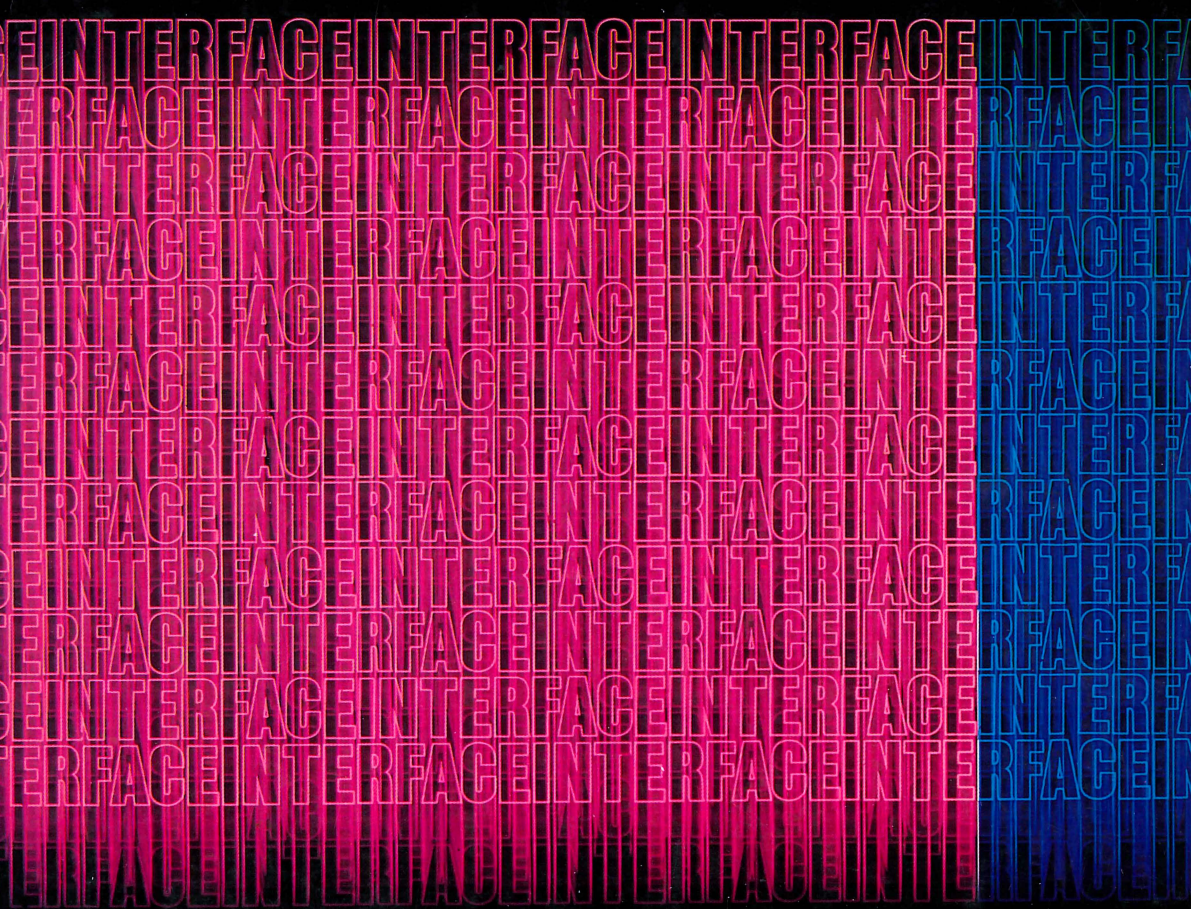
RICHARD C. HALLGREN

interface projects for the apple II



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RICHARD C. HALLGREN

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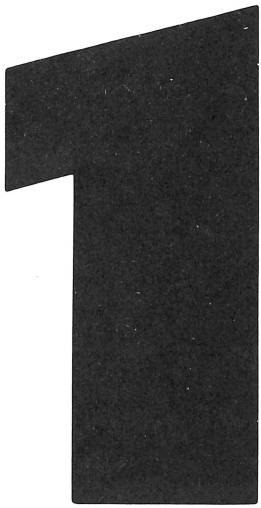
Richard C. Hallgren, Ph.D., is an assistant professor at Michigan State University. He has written numerous articles and books, including INTERFACE PROJECTS FOR THE TRS-80, published by Prentice-Hall.



INTRODUCTION

The rapid expansion of the electronics industry and their ability to mass produce reliable, large-scale integrated circuits has led to the reality of scientific calculators and multifunction digital watches for under $20 and "personal computers" starting from $200. In 1971 the Intel Corporation had the honor of initiating this revolution by introducing the first commercially available microprocessor. While the performance of this device was limited by its relatively slow central processing unit and its use of a 4-bit data bus, its acceptance was so dramatic that within a two-year period the cost of a single unit had dropped from $200 to under $20. Today, it is a rare individual who does not have a microprocessor (if not a personal computer) of some type in his or her home.

As I have talked to owners of personal computers, it has become apparent that there is a certain group of individuals who

would like to use their machines as extensively as is possible, both at home and at their place of employment. This inevitably results in the need for interface circuitry to allow the computer to be connected to external devices allowing users to monitor and control their environment. On the basis of the response of readers to several articles that I have written, I have come to the conclusion that there is a great need for a book that covers not only the theory behind interfacing a computer to external devices but also gives a broad selection of interface circuits that can be built and expected to work. What I have attempted to do is to provide you, the reader, with a number if examples of interface circuits ranging from the very simple to the somewhat complicated. I have included software for each circuit and can assure you that both the hardware and the software have not only been tested together but have been used in some practical area of application. The result is a document that explains the theory behind computer interfacing and gives you the choice of either building the circuit as is or modifying it to meet your specific needs. The hardware for these projects was designed and the components selected so that construction and check-out would be a straightforward matter. The circuits have been chosen to offer something of interest and application to a broad range of individuals: the hobbyist, the experimenter, the manager of a manufacturing plant, and the engineer or scientist in a research facility. The intent being to enable people to more fully use the computational and control capabilities of their personal computer in a practical and interesting way.

The book assumes that readers have a fairly good understanding of the commands in Applesoft BASIC, and have written some of their own programs. Since some of the supporting software will be using 6502 machine code, the reader is encouraged to become familiar with the 6502 instruction set. Programing examples using both Applesoft and 6502 machine language have been provided throughout the book. While construction of the circuits is straightforward, it should be understood that a certain amount of experience, and a certain level of expertise is expected. Previous construction of a commercial kit would probably qualify most individuals. So, with all this in mind, let's get started with the job of connecting your Apple II to the outside world.

REVIEW OF DATA TRANSFER FORMATS

BASIC INTERFACE CONCEPTS

Before we get into actual circuit designs, we need to spend some time reviewing basic interface concepts. Even experienced circuit designers should read this section to become familiar with terminology that will be used.

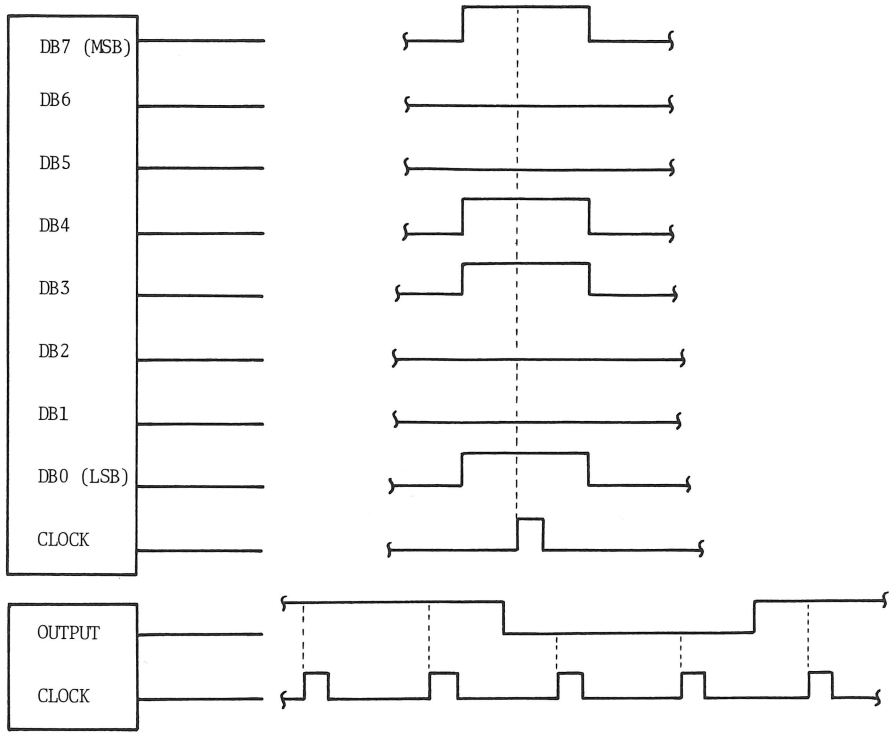
We can define an input/output (I/O) port as a collection of electronic circuits, under the control of the computer, which routes data to and from an external peripheral device. The key words in this definition are *data* and *external*. The route by which the data flow to or from the external device is called the *port*. A line printer is an example of an external device; the computer sends characters to be printed to the printer and, in some cases, the printer sends control signals back to the computer. The pur-

pose of these signals is to regulate the flow of the data. This interaction is called *handshaking.*

Ports can be constructed so that data are handled in either a serial or a parallel format (Figure 2.1).

Parallel transfer of data involves the mass transfer, at a given point in time, of several bits of data, where the number of bits transferred is usually equal to the word size of the computer. For the Apple II this is equal to 8 bits. In general, the number of bits transferred at one time will be equal to the size of the data bus. For example, if we were working with a Z8000, which has a 16-bit data bus, a parallel transfer would involve 16 bits. When high rates of data transfer are desired, such as data transfer between a computer and a floppy disk, the transfer is usually handled with a parallel format. Computers handle parallel communication rela-

FIGURE 2.1 Comparison of parallel and serial format. The clock impulse is used to signal the external device that the signals are stable. For both examples, the data word being transmitted is binary 10011001.



tively easily and, even though multiconductor cables are required, the total expense is not great because the distance between devices is usually quite short.

Serial transfer of data involves transmitting individual bits of data, one bit at a time. Microcomputers do not normally communicate in a serial format, so there is usually not a single machine language command that facilitates this type of operation. Therefore, we need to add either a software subroutine or a new piece of hardware to accomplish a serial transfer of data. Such an addition results in increased system expense, but gives the capability of transferring data over increased distances at relatively high data rates. The Electronics Industry Association (EIA) RS-232C electrical specification for serial transfer of data is the standard for industrial applications. This specification defines the following voltage levels: A logic level 1 is called a *mark* and is considered to be any voltage level more negative than −3 volts. A logic level 0 is called a *space* and is considered to be any voltage level more positive than +3 volts. In general, designers use +12 and −12 volt levels for the logic 0 and logic 1 states. In addition to specifying voltage levels, the EIA also defines the standard RS-232C connector to be a 25-pin, D subminiature type (commonly referred as a DB-25). The pin assignments and their functions are listed in Table 2.1.

Before we look at specific examples, we should take a look at the architecture of the 6502 to determine how we can communicate in an orderly manner with several peripheral devices that may be connected to the same data bus and to the same address bus. The Apple II computer uses a 6502 type microprocessor to perform the logical, mathematical, and decision-making operations necessary for high-speed operation of the computer. This microprocessor is an 8-bit device which combines the bus structure of the 6501 microprocessor (16-bit address bus, 8-bit bidirectional data bus, and two interrupts) with an instruction set that includes over 150 different commands. The bidirectional data bus is used to transfer information both to and from the central processing unit. The 16-bit address bus has the capability of uniquely defining 65,536 addressable locations. The 6502 generates several control signals which are used both internally and externally to supervise and manage the flow of information. Since data can only flow in one direction at a time, and since the data are usually

TABLE 2.1 EIA standards for DB-25 connector pin assignments when used for communication between RS-232C systems.

Pin 1	PGND - Protective Ground This is chassis or equipment ground. It may also be tied to signal ground.
Pin 2	TD - Transmit Data This is the serial data from the terminal to the remote receiving equipment. When no data is being sent it is in a marking (1) condition.
Pin 3	RD - Receive Data This is the serial data from the remote equipment which is transmitted to the terminal.
Pin 4	RTS - Request to Send Controls the direction of data transmission. In full-duplex operation an "on" sets transmit mode and an "off" sets non-transmit mode. In half-duplex operation an "on" inhibits the receive mode and an "off" enables it.
Pin 5	CTS - Clear to Send Signal from the modem to the terminal indicating ability to transmit data. An "on" is "Ready" and an "off" is "not ready."
Pin 6	DSR - Data Set Ready Signal from the modem to the terminal. An "on" condition indicates that the modem is ready.
Pin 7	SGND - Signal Ground
Pin 8	CD - Carrier Detect An "on" indicates reception of a carrier from the remote data set; "off" indicates no carrier is being received.
Pin 20	DTR - Data Terminal Ready "On" connects the communication equipment to the communications channel; "off" disconnects the communications equipment from the communications channel.
Pin 22	RI - Ring Indicator An "on" indicates that a ringing signal is being received on the communications channel.

directed to a specific device or memory location, these control lines provide an essential coordinating function.

Figure 2.2 shows the pin configuration for the 6502. The 6502 belongs to the one-address architectural class of microprocessors; that is, all memory-related instructions refer to a single memory location. The direction of all data transfers is controlled by the READ/WRITE* (R/W*) line. When this line goes low, all data transfers will occur in the direction from the processor to memory. When it goes high, all data transfers will occur in the direction from memory to the processor. The timing of all data transfers is controlled by the system clock. The clock system used by the 6502 is referred to as *two-phase;* it is most easily thought of as two nonoverlapping square waves. When the microprocessor is reading a data byte from memory, the address of the desired memory location is placed on the address bus during the phase one clock pulse. Information stored in that particular memory location is strobed onto the data bus and into the accumulator

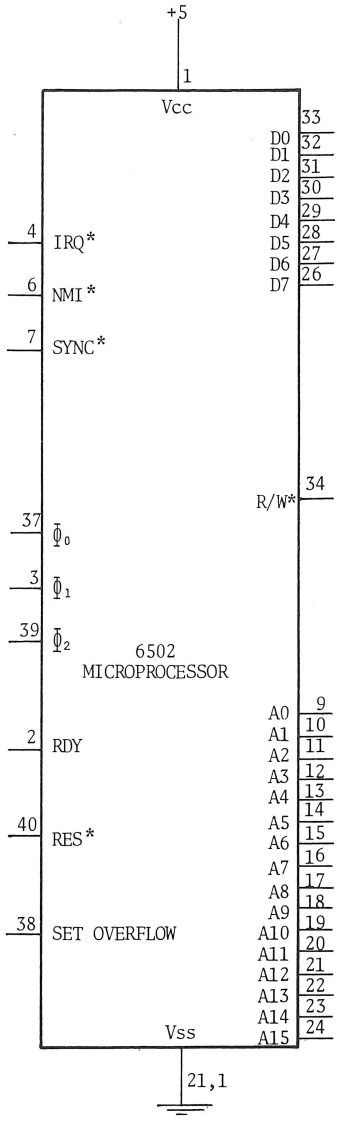


FIGURE 2.2 6502 pin configuration.

during the phase two clock pulse. Data being written to memory is handled by a reversed set of operations.

Fortunately for the individual who wishes to interface the Apple II to external devices, the designer of the computer has provided eight peripheral-board connectors on the mother board. Having these connectors on the mother board allows you to place

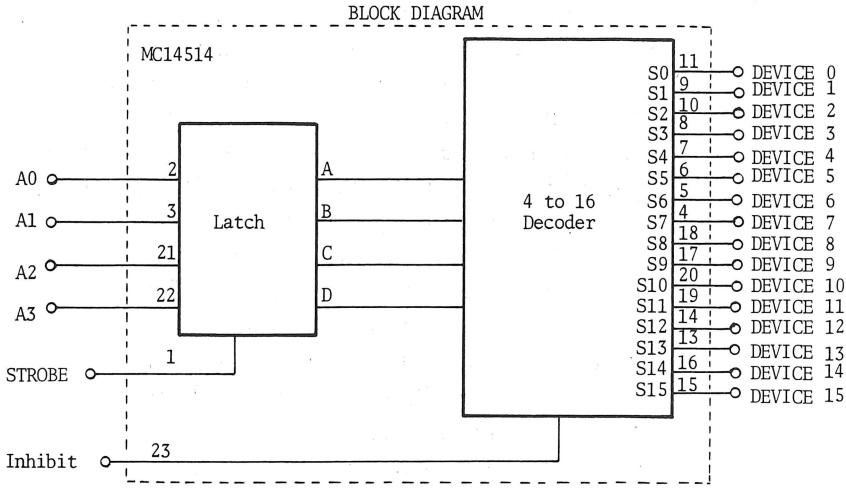
TABLE 2.2 Peripheral I/O location address assignments.

Hex Address	Assigned Function	Comments
C080-C08F	Device Select #0	Pin #41 (DS*) on the selected peripheral connector goes low during phase two of the clock.
C090-C09F	Device Select #1	
C0A0-C0AF	Device Select #2	
C0B0-C0BF	Device Select #3	
C0C0-C0CF	Device Select #4	
C0D0-C0DF	Device Select #5	
C0E0-C0EF	Device Select #6	
C0F0-C0FF	Device Select #7	

any interface boards that you construct inside the computer's case, and permits you to use the Apple's power supply. The peripheral-board connectors give the hardware designer access to all address, data, and control lines. In addition, certain control and address lines have been decoded to provide the designer with a device select (DS*) signal. What this means is that each peripheral connector has a unique range of address locations that will result in a low output on the DS* line. Since DS* goes low during the phase two clock pulse, it is convenient to use this as a data strobe pulse during either a READ or WRITE operation. Table 2.2 shows the address locations that are assigned to each of the eight peripheral connectors.

Since each peripheral connector can address up to sixteen devices, and since we will not exhaust this capability on any one of the projects that you will be building, I will limit my comments here to one peripheral connector, specifically peripheral I/O location 7. In Chapter 5, however, I will design the digital plotter interface so that it resides in I/O location 5. I will do this so that the high speed A/D converter and the digital plotter can be used to digitize and plot data without having to switch the physical location of the circuit boards. Figure 2.3 shows a simple but effective method for decoding the four least significant bits of the address bus into sixteen unique control lines. For normal operation, the INHIBIT control line would remain low. Upon execution of either a READ or WRITE command, the device control signal (DS*), connected to the STROBE control line, would be used to strobe the current contents of the address bus into the decoder. The decoded output would then be used to indicate to a specific external circuit that the data bus was available for its specific use. In the next section we will see how we can use the R/W* control line to direct the flow of data to and from our interface projects.

FIGURE 2.3 4-16 line address decoder. Each device is selected by a unique combination of the address lines A0-A3.



DECODE TRUTH TABLE (Strobe = 1)

INHIBIT	DATA INPUTS A3	A2	A1	A0	SELECTED OUTPUT LOGIC "1"
0	0	0	0	0	Device 0
0	0	0	0	1	Device 1
0	0	0	1	0	Device 2
0	0	0	1	1	Device 3
0	0	1	0	0	Device 4
0	0	1	0	1	Device 5
0	0	1	1	0	Device 6
0	0	1	1	1	Device 7
0	1	0	0	0	Device 8
0	1	0	0	1	Device 9
0	1	0	1	0	Device 10
0	1	0	1	1	Device 11
0	1	1	0	0	Device 12
0	1	1	0	1	Device 13
0	1	1	1	0	Device 14
0	1	1	1	1	Device 15
1	X	X	X	X	All Outputs = 0

X = Don't Care

PARALLEL DATA FORMAT

Transmission and reception of data in a parallel format combines the advantages of high transfer rates and low cost. As mentioned earlier, parallel data transfer involves the mass movement of several bits of data at one time. It becomes a relatively straightforward task to construct both input and output ports since all the control, data, and address lines that we will need are available on the Apple II peripheral I/O connector (see Figure 2.4). Table 2.3 lists the signals appearing on this connector and their functions. Figures 2.5a and 2.5b show examples of practical circuits which could be connected directly to the I/O connector 7, providing one 8-bit input port and one 8-bit latched output port. To transfer data from the accumulator to the latched output port, you need only to perform the BASIC statement POKE-16143,X or the machine language commands LDA #$X and STA $C0F1. The microprocessor performs the following bit transfers when you execute either of these commands:

1. The device address (C0F1) is strobed onto the address bus.
2. The contents of the accumulator (X) are strobed onto the data bus.

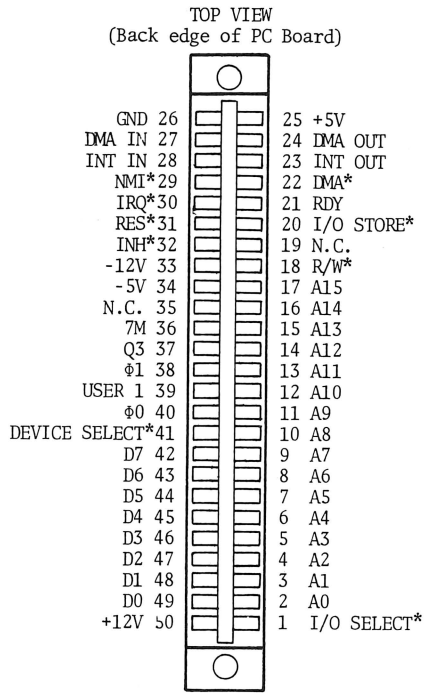


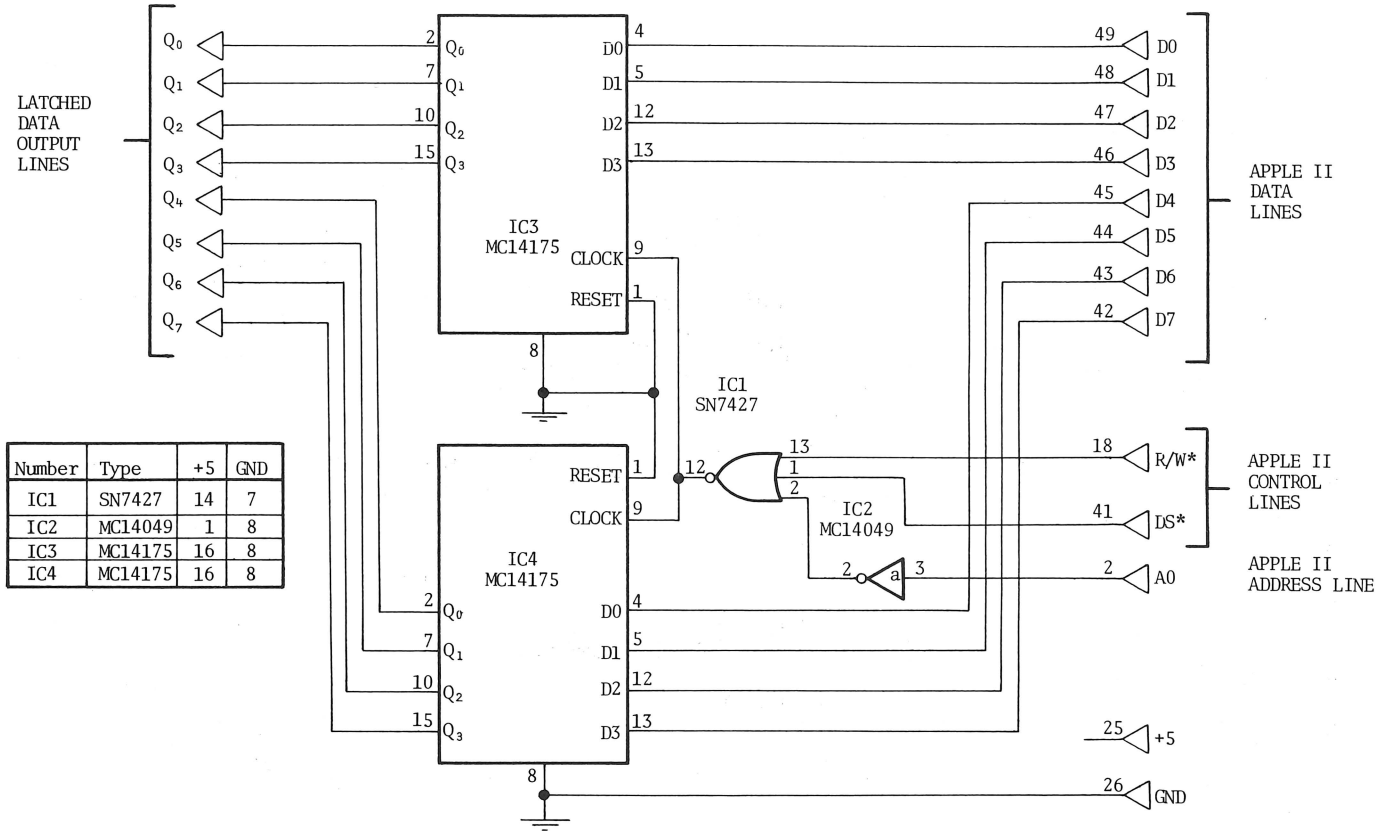
FIGURE 2.4 Output pin configuration for the Apple II peripheral I/O connector. Refer to Table 2.3 for a description of each pin.

TABLE 2.3 Functional description of pins on the Apple II peripheral I/O connector.

P/N	Signal Name	Description
1	I/O SELECT*	Peripheral I/O Select Line
2	A0	Address Output
3	A1	Address Output
4	A2	Address Output
5	A3	Address Output
6	A4	Address Output
7	A5	Address Output
8	A6	Address Output
9	A7	Address Output
10	A8	Address Output
11	A9	Address Output
12	A10	Address Output
13	A11	Address Output
14	A12	Address Output
15	A13	Address Output
16	A14	Address Output
17	A15	Address Output
18	R/W*	System Read/Write Strobe
19	N.C.	No Connection
20	I/O STRBE*	Peripheral I/O Strobe Line
21	RDY	Peripheral Device Ready
22	DMA*	Direct Memory Access Line
23	INT OUT	Interrupt Chain Output
24	DMA OUT	Direct Memory Access Chain Output
25	+5	Positive 5-Volt Supply
26	GND	Power Supply Ground
27	DMA IN	Direct Memory Access Chain Input
28	INT IN	Interrupt Chain Input
29	NMI*	Non Maskable Interrupt
30	IRQ*	Interrupt Request Line
31	RES*	Reset Line
32	INH*	Inhibit Line
33	-12	Negative 12-Volt Supply
34	-5	Negative 5-Volt Supply
35	N.C.	No Connection
36	7M	7 MHZ Clock
37	Q_3	1 MHZ Timing Signal
38	Φ1	Phase 1 Clock Signal
39	USER 1	Disables Internal I/O Adr Decode
40	Φ0	Phase 0 Clock Signal
41	DS*	Device Select Line
42	D7	Bidirectional Data Bus
43	D6	Bidirectional Data Bus
44	D5	Bidirectional Data Bus
45	D4	Bidirectional Data Bus
46	D3	Bidirectional Data Bus
47	D2	Bidirectional Data Bus
48	D1	Bidirectional Data Bus
49	D0	Bidirectional Data Bus
50	+12	Positive 12-Volt Supply

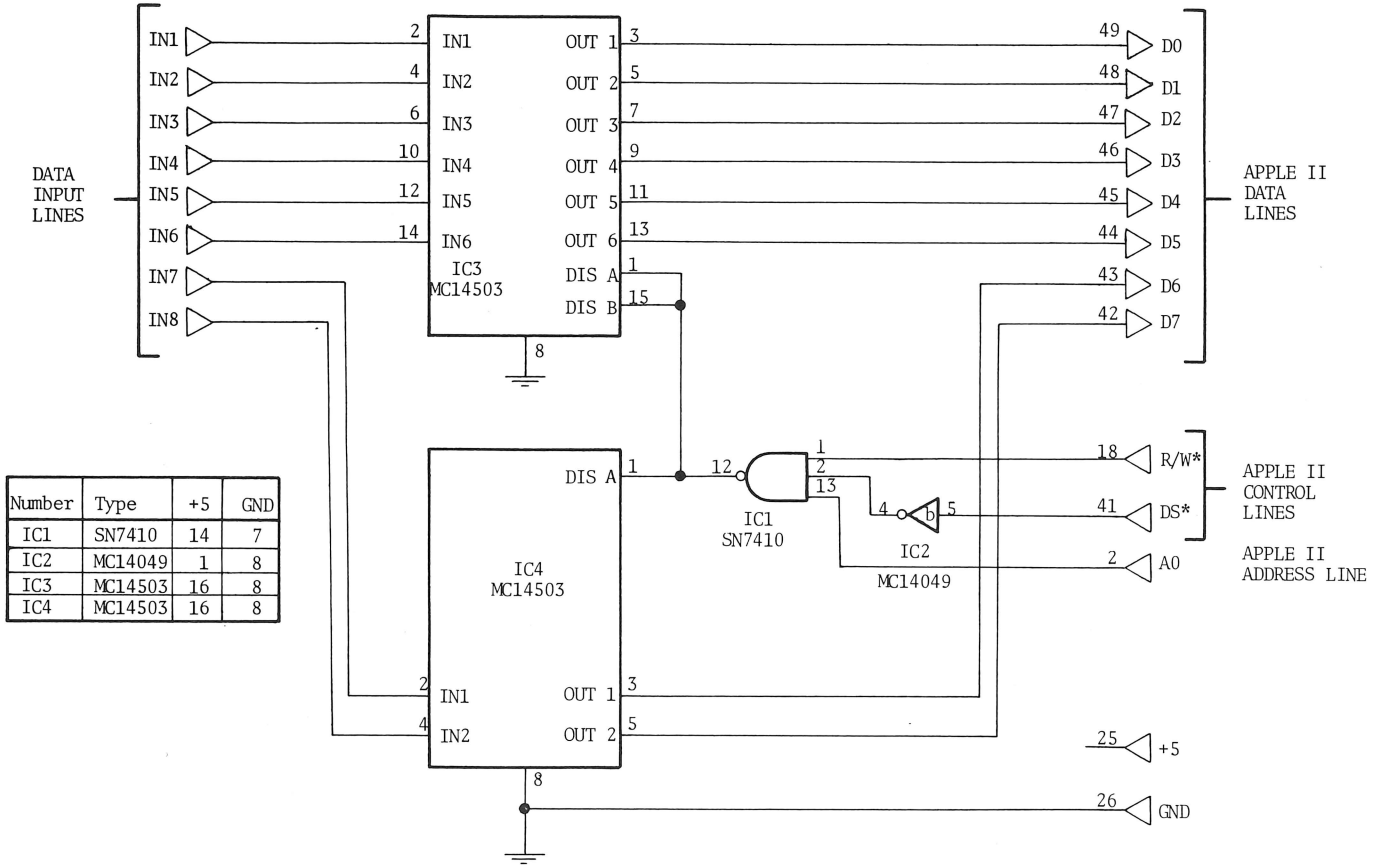
Note: "*" means logical "Ø" true input or output.

Since the data are valid for only a few clock cycles (perhaps 500 ns.), a set of clocked flip-flops (IC3 and IC4) are provided so that the data are latched and consequently stable, until the next command to write data to this port is executed. The circuit works in the following manner:



Number	Type	+5	GND
IC1	SN7427	14	7
IC2	MC14049	1	8
IC3	MC14175	16	8
IC4	MC14175	16	8

FIGURE 2.5a Circuit diagram of a typical parallel output port. Performing a POKE -16143,16 would cause the DS* and R/W* control lines to go low, address line A0 to go high, and 16_{10} to be latched into the output register.



Number	Type	+5	GND
IC1	SN7410	14	7
IC2	MC14049	1	8
IC3	MC14503	16	8
IC4	MC14503	16	8

FIGURE 2.5b Circuit diagram of a typical parallel input port. Performing a PEEK (-16143) would cause the DS* control line to go low, the R/W* control line to go high, address line A0 to go high, and the data on the input lines to be transferred into the accumulator.

1. Whenever address line A0 is high and the DS* line and the R/W* line are low, there will appear an output strobe pulse on pin 12 of IC1.
2. Whenever this strobed output pulse appears, the contents of the data bus will be transferred into the clocked flip-flops, and will appear on the latched data output lines.

External devices transferring data into the computer can be connected directly to the data bus, but to add an additional margin of safety (that is, to help keep you from "smoking" your computer), I have included a 3-state buffer. The 3-state buffer is used as a gate which allows signals from the peripheral device to be placed on the data bus at an appropriate time. To transfer data from an external device into the accumulator, you need only to perform the BASIC statement PEEK(-16143), or the assembly language command LDA $C0F1. The microprocessor performs the following bit transfers when you execute either of these commands:

1. The device address (C0F1) is strobed onto the address bus.
2. The contents of the data bus are strobed into the accumulator (A).

The circuit works in the following manner:

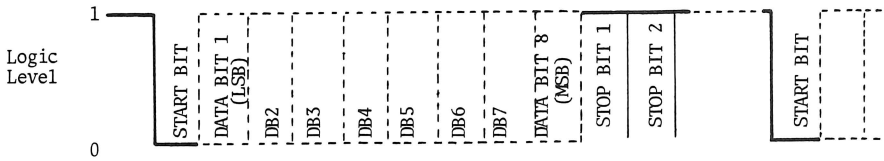
1. Whenever address line A0 is high, control line DS* is low, and control line R/W* is high, there will appear a strobe pulse on pin 12 of IC1.
2. Whenever this strobed input pulse appears, the 3-state buffer will connect the data input lines to the data bus.

SERIAL DATA FORMAT

When considering a computer interface project involving a fairly large distance between the computer and the device to be interfaced, we begin to realize problems in trying to use a parallel data transfer scheme. First, there is the expense and inconvenience of running a multiconductor cable over long distance. There is also the problem of noise which gets introduced into the data, control, and address lines. While this noise can be reduced with filters, or current level signals can be used, it is often more convenient to

use a serial format for the transmission of control and data bits. With serial transmission, individual bits are transmitted over a pair of wires one bit at a time. The receiving device collects the bits and reconstructs them into a single computer word which, for the Apple II, is equal to 8 bits. Since the computer normally processes data in a parallel format, the transmitting device must perform a parallel-to-serial conversion, and the receiving device must perform a serial-to-parallel conversion. Obviously, the transmission speed and the bit format must be well-defined, and there must be some way to synchronize the serial bit flow so that the receiving device knows where each data word begins. The most common format for serial transmission is called *asynchronous-serial.* Because it is self-clocking—that is, it contains a special bit pattern that allows the receiving device to know exactly where a new data word begins—the cable connecting a peripheral device with the computer needs to have only two signal lines and one ground line. Figure 2.6a shows the format for the transmission of a data word in an asynchronous-serial format. The START bit, a logic 1 to logic 0 transition, is used to alert the receiving circuitry that a new data word in going to be sent. The receiver waits for one-half of a bit period and then samples the input again. If the input line is still a logic 0, the receiver assumes that it has detected a "real" START bit and not a fluctuation due to noise on the line. The receiving device then waits one bit period and samples the input line to determine whether data bit 1 is a logic 1 or a logic 0. By periodically waiting one bit period and sampling the input line, the remainder of the data bits are obtained. The two STOP bits then signal the receiving device that it has reached the end of the data word. Having transferred the data word into the computer, the device starts looking for the next START bit. Figure 2.6b shows the actual bit pattern that results when the data word 10011101 is transmitted.

FIGURE 2.6a Typical asynchronous-serial bit pattern for the transmission of an 8-bit data word with 2 stop bits.



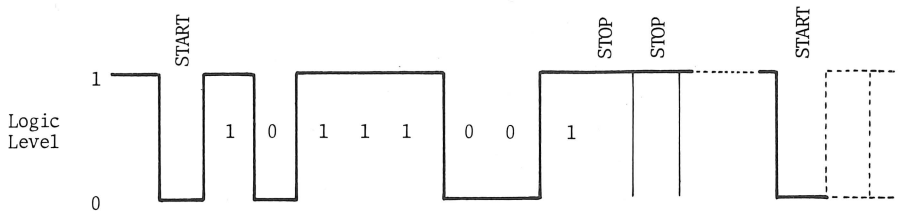
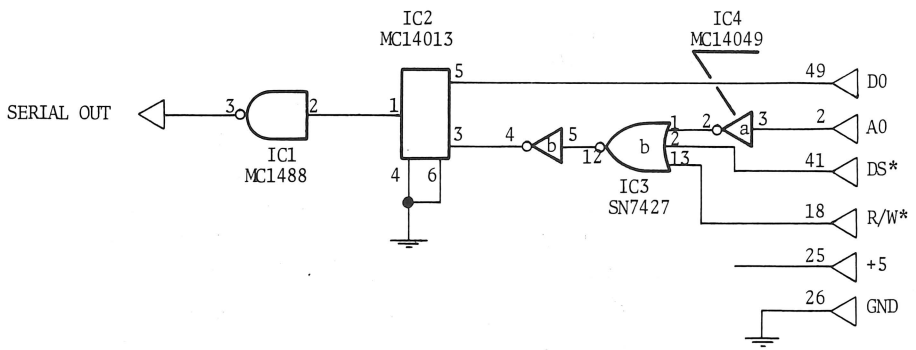


FIGURE 2.6b Logic levels plotted as a function of time during the asynchronous-serial transmission of the 8-bit data word, 10011101_2.

The asynchronous-serial protocol allows the use of either 5,6,7, or 8 data bits along with either 1 or 2 STOP bits. The examples we will be using will be formatted so as to transmit and receive 1 START bit, 8 data bits, and 2 STOP bits. The bit transfer rate can be set to 110, 150, 300, 600, 1200, 2400, 4800, and 9600 bits per second; the actual value depending upon the application.

Figure 2.7 shows a circuit which converts TTL voltage levels to RS232-C voltage levels, and which can be used with the program shown in Listing 2.1 to accomplish a parallel-to-serial output.

FIGURE 2.7 TTL to RS232-C interface.



Number	Type	+5	+12	-12	GND
IC1	MC1488	--	14	1	7
IC2	MC14013	14	--	--	7
IC3	SN7427	14	--	--	7
IC4	MC14049	1	--	--	8

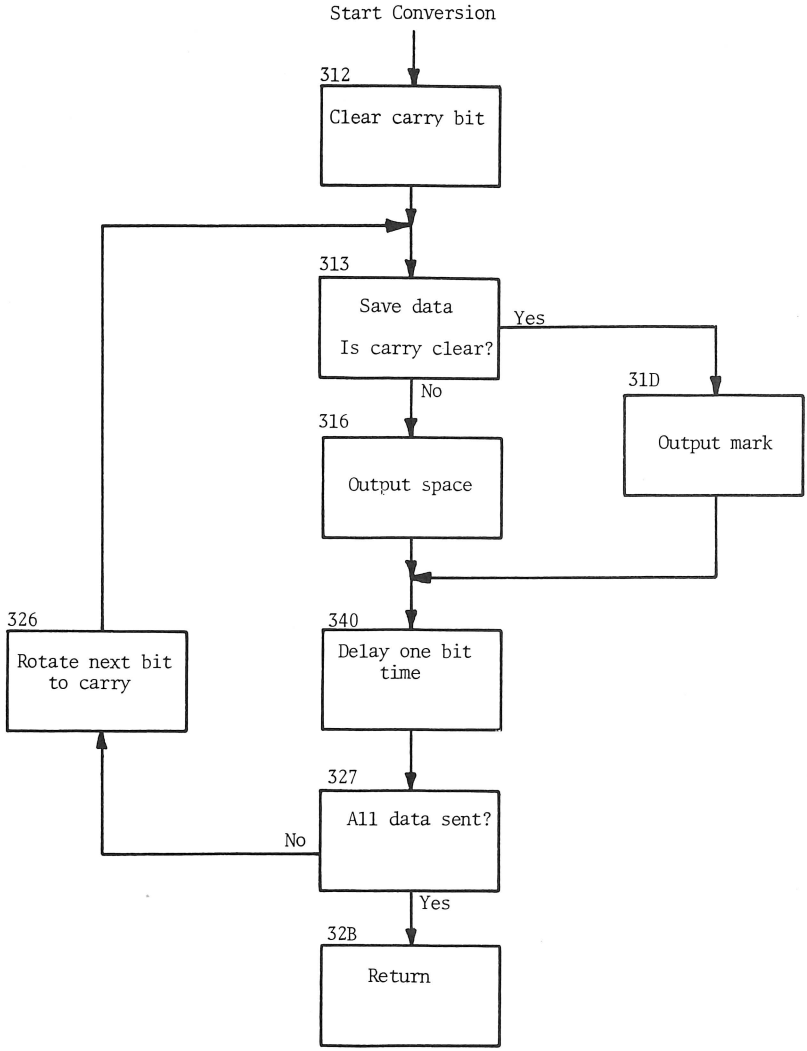
LISTING 2.1 Subroutine for parallel-to-serial output. Program assumes that the character to be sent will be in the A register.

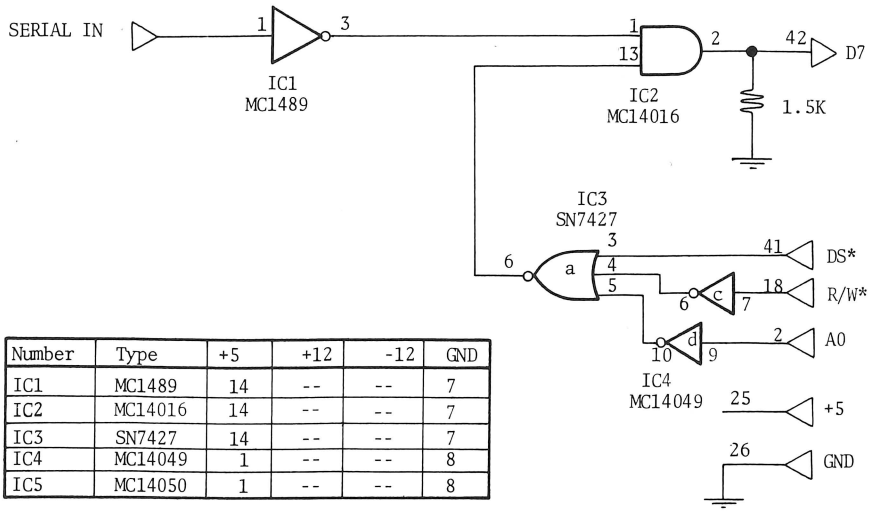
```
30F   08          PHP             SAVE STATUS
310   A0 B0       LDY   #$0B      11 BITS
312   18          CLC             CLEAR CARRY
313   48          PHA             SAVE A REGISTER
314   B0 07       BCS   $31D
316   A9 00       LDA   #$00      SEND A SPACE
318   8D F1 C0    STA   $C0F1
31B   90 05       BCC   $322
31D   A9 01       LDA   #$01      SEND A MARK
31F   8D F1 C0    STA   $C0F1
322   20 40 03    JSR   $340      JUMP TO DELAY
325   68          PLA             RESTORE A REGISTER
326   6A          ROR             ROTATE A REGISTER
327   88          DEY             ALL BITS SENT?
328   D0 E9       BNE   $313       BRANCH IF NOT
32A   28          PLP             RESTORE STATUS
32B   60          RTS             RETURN


340   A9 4D       LDA   #$4D      LOAD A REGISTER
342   48          PHA             SAVE A REGISTER
343   A9 20       LDA   #$20      LOAD A REGISTER
345   4A          LSR             SHIFT A REGISTER
346   EA          NOP
347   90 FC       BCC   $345
349   68          PLA             RESTORE A REGISTER
34A   E9 01       SBC   #$01      SUBTRACT 1
34C   D0 F4       BNE   $342
34E   60          RTS             RETURN
```

When a STA $C0F1 of machine language command is executed, the contents of the least significant bit of the (data bit 0_0) accumulator are latched into the output of the D-type flip-flop (IC2). Figure 2.8 shows a flow chart for the TTL to RS232-C program.

Figure 2.9 shows a circuit which can be used to convert RS232-C voltage levels to TTL levels, and which can be used with the program shown in Listing 2.2 to accomplish a serial-to-parallel conversion. When a LDA $C0F1 machine language command is executed, the voltage level appearing on the SERIAL IN line will be strobed into data bit D7 of the accumulator. Figure 2.10 shows a flow chart for the RS232-C to TTL program. Timing for both subroutines results in a baud rate of 300 bits per second. The serial output subroutine (Listing 2.1) expects the character which is to be sent to be stored in the accumulator. The serial input subroutine (Listing 2.2) will terminate with the received character displayed on the video monitor. We will put both of these circuits to use in Chapter 5 where we will see how to use the Apple II in serial applications.

FIGURE 2.8 Flow chart for the TTL to RS232-C program.





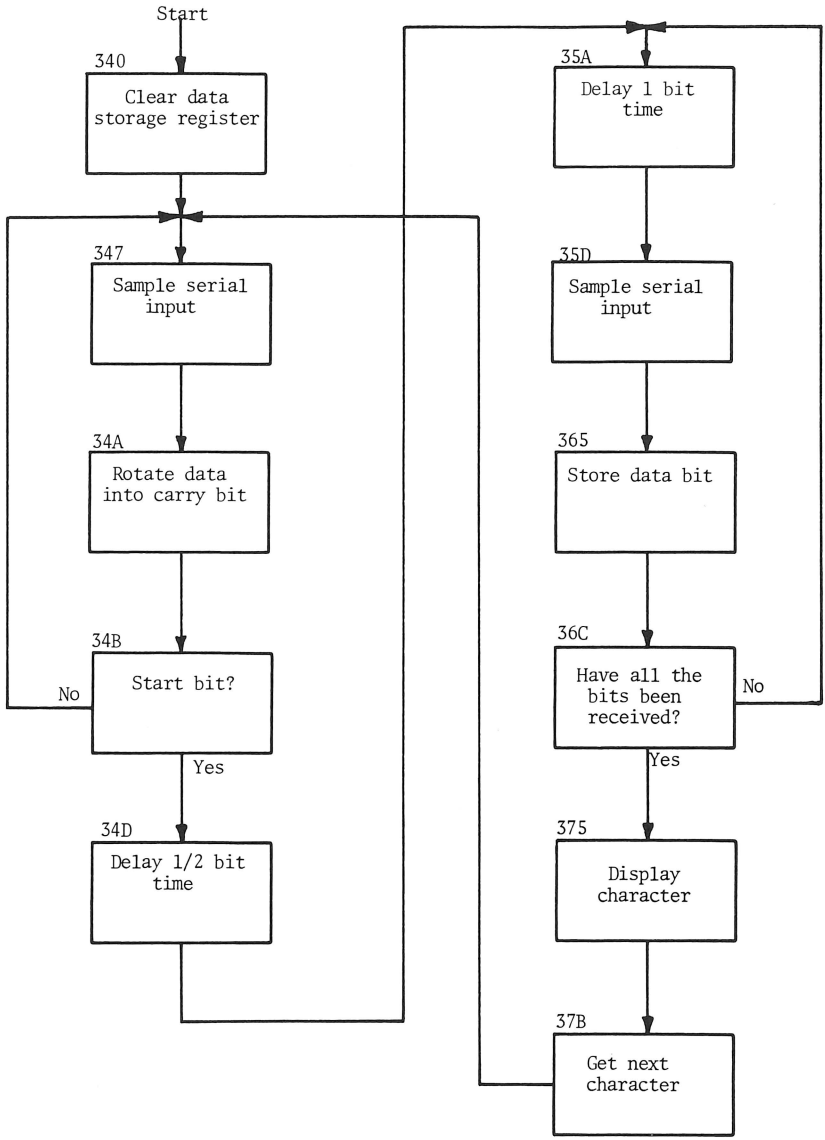
Number	Type	+5	+12	-12	GND
IC1	MC1489	14	--	--	7
IC2	MC14016	14	--	--	7
IC3	SN7427	14	--	--	7
IC4	MC14049	1	--	--	8
IC5	MC14050	1	--	--	8

FIGURE 2.9 RS232-C to TTL interface.

LISTING 2.2 Subroutine for serial-to-parallel conversion. Program displays the received character on the video display.

```
330    A9 4D       LDA  #$4D     LOAD A REGISTER
332    48          PHA           SAVE A REGISTER
333    A9 20       LDA  #$20     LOAD REGISTER
335    4A          LSR           SHIFT RIGHT
336    90 FD       BCC  $335     JUMP IF NOT ZERO
338    68          PLA           RESTORE A REGISTER
339    E9 01       SBC  #$01     SUBTRACT ONE
33B    D0 F5       BNE  $332     JUMP IF NOT ZERO
33D    60          RTS           RETURN
33E    EA          NOP
33F    EA          NOP
340    A9 00       LDA  #$00     LOAD A REGISTER
342    8D 80 03    STA  $380     TEMP A REGISTER
345    A2 08       LDX  #$08     8 DATA BITS
347    AD F1 C0    LDA  $C0F1    GET RECEIVED CHARACTER
34A    2A          ROL           ROTATE LEFT
34B    B0 B3       BCS  $340     NO CHARACTER RECEIVED
34D    A9 26       LDA  #$26     1/2 CHARACTER DELAY
34F    48          PHA
350    A9 20       LDA  #$20
352    4A          LSR
353    90 FD       BCC  $352
355    68          PLA
356    E9 01       SBC  #$01
358    D0 F5       BNE  $34F
35A    20 30 03    JSR  $330     JUMP TO DELAY
35D    AD F1 C0    LDA  $C0F1    GET CHARACTER
360    29 80       AND  #$80     GET MSB
362    0D 80 03    ORA  $380     OR A REGISTER WITH TEMP
365    8D 80 03    STA  $380     SAVE IN TEMP
368    18          CLC           CLEAR CARRY
369    6E 80 03    ROR  $380     ROTATE TEMP RIGHT
36C    CA          DEX           ALL BITS RECEIVED?
36D    D0 EB       BNE  $35A     BRANCH IF NOT
36F    09 80       ORA  #$80     SET MSB
371    C9 C0       CMP  #$C0     CHECK FOR CONTROL CHARAC
373    F0 03       BEQ  $378     JUMP IF NOT
375    20 FD FB    JSR  $FBFD    DISPLAY ON VIDEO
378    20 30 03    JSR  $330     JUMP TO DELAY
37B    4C 00 03    JMP  $340     GET NEXT CHARACTER
```

FIGURE 2.10 Flow chart for the RS232-C to TTL converter.



3

SAMPLING THE EXTERNAL WORLD

Now that we have covered some background material relative to the operation of the Apple II computer, we can proceed to the "fun" part of computer operation, the part that involves the evaluation of a need, and the construction of a circuit to meet that need. We will be progressing from examples that are very simple to examples that are somewhat complicated; with the confidence that once you can build and use simple circuits, you will be able to build and use the more complicated ones. In Appendix A I have made a personal appraisal of several construction techniques which you may want to consider; it may be to your advantage to review this material at this time.

STATUS OF A BINARY SIGNAL

For some applications we will want to be able to sample an input port to determine the status or state of an external device. For example, we might want to know if a device was turned on, a valve opened, or a switch closed. Figure 3.1 shows a schematic of a circuit which will allow you to test the state of six switches. When a X= PEEK(-16143) BASIC command is executed, a voltage level, which is a function of whether each individual switch is open or closed, will be strobed into the computer. The variable X can then be decoded to determine the status of each switch. You might use such a circuit to allow external control of a program which is being executed, or to take an action which would be consistent with the state of the switch. The switches might be simple toggle switches mounted on a panel, or they might be relay switches associated with some automated process that you want to monitor. Figure 3.2 shows a flow chart for a BASIC program which will test the status of each switch and display that status on the video display. Listing 3.1 shows the program with comments. This program is intended to be called as a subroutine, and is set up so that if the status has not changed, control will return to the calling routine.

While I have used mechanical toggle switches for this example, the application could be easily extended to the following:

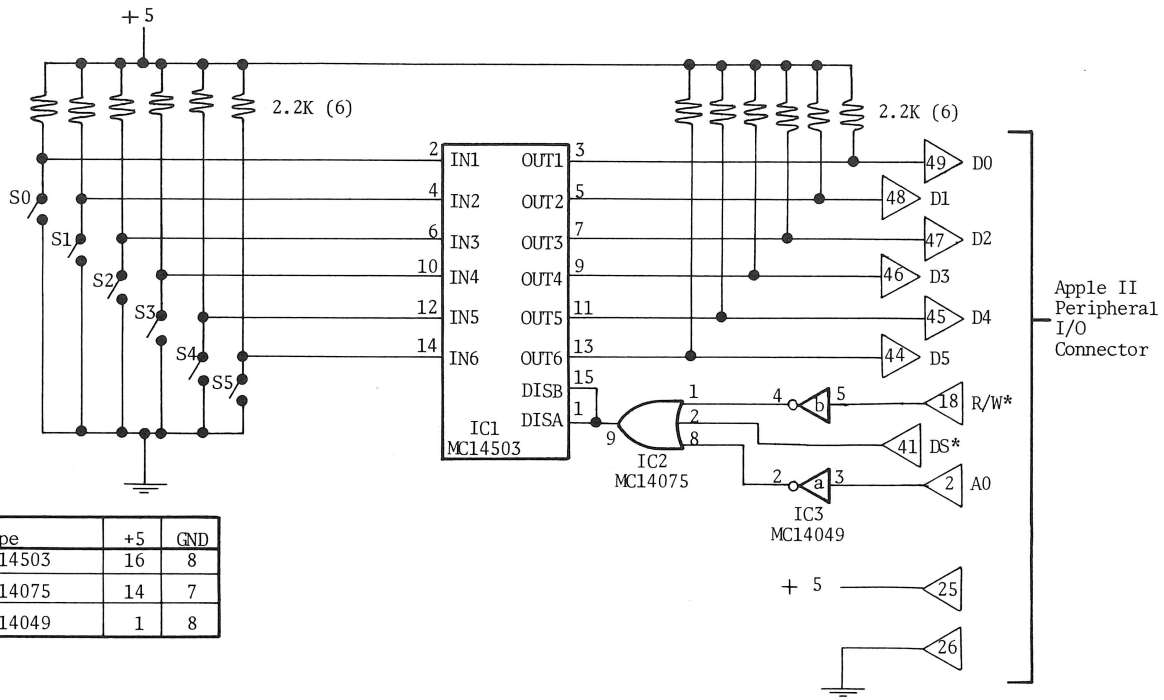
1. Water level sensing switches
2. Displacement sensing microswitches
3. Light sensitive, photoswitches
4. Temperature sensitive, bimetallic switches
5. Motor relay switches

An advantage of using the computer to sense and respond to the status of a switch lies in its ability to be reprogrammed easily when the application changes.

ANALOG-TO-DIGITAL CONVERSION

Background

There are many applications where we will want to have our computer system "measure" some parameter which varies as a function of time. In most cases, we will be using some type of



Number	Type	+5	GND
IC1	MC14503	16	8
IC2	MC14075	14	7
IC3	MC14049	1	8

FIGURE 3.1 Schematic of switch status input port.

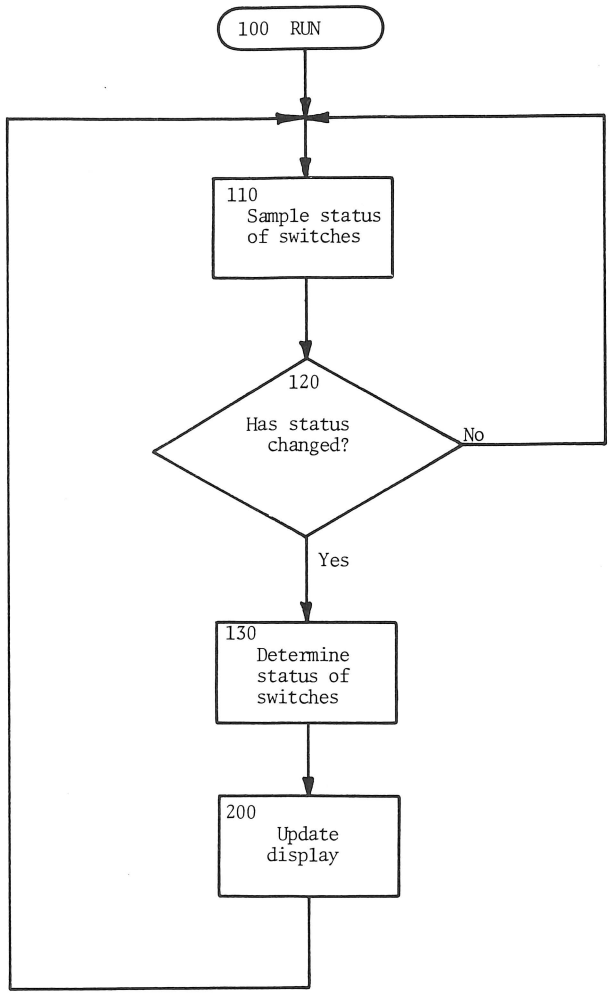


FIGURE 3.2 Flow chart of switch status program.

transducer which takes a physical parameter such as temperature, pressure, strain, or position, and converts it into an electrical voltage or current. While computers are quite proficient when handling binary voltages, they are not directly able to handle the type of analog voltages that will be coming from the transducers we will be using. To resolve this problem we need to build an interface called an analog-to-digital (A/D) converter. Our design criteria will be primarily concerned with determining appropriate values, based on our particular application, for resolution

LISTING 3.1 BASIC program for determining and displaying switch status.

```
100  REM  SWITCH STATUS ROUTINE
102  REM  APPLE II, R. HALLGREN, 10-20-81
104  X1=0
110  REM  SAMPLE SWITCH STATUS
112  X=PEEK(-16143)
120  REM  STATUS CHANGED?
122  IF X>127 THEN X=X-128
124  IF X>63 THEN X=X-64
126  IF X=X1 THEN GOTO 110
130  REM  DETERMINE SWITCH STATUS
132  X1=X:IF X>31 THEN D5=1:X=X-32:GOTO 140
136  D5=0
140  IF X>15 THEN D4=1:X=X-16:GOTO 150
142  D4=0
150  IF X>7 THEN D3=1:X=X-8:GOTO 160
152  D3=0
160  IF X>3 THEN D2=1:X=X-4:GOTO 170
162  D2=0
170  IF X>1 THEN D1=1:X=X-2:GOTO 180
172  D1=0
180  IF X=1 THEN D0=1:GOTO 184
182  D0=0
184  IF D0=1 THEN D0$="ON"
185  IF D0=0 THEN D0$="OFF"
186  IF D1=1 THEN D1$="ON"
187  IF D1=0 THEN D1$="OFF"
188  IF D2=1 THEN D2$="ON"
189  IF D2=0 THEN D2$="OFF"
190  IF D3=1 THEN D3$="ON"
191  IF D3=0 THEN D3$="OFF"
192  IF D4=1 THEN D4$="ON"
193  IF D4=0 THEN D4$="OFF"
194  IF D5=1 THEN D5$="ON"
195  IF D5=0 THEN D5$="OFF"
200  REM UPDATE DISPLAY
210  HOME
212  PRINT "*********************************************"
222  PRINT "*"
226  PRINT "*                  SWITCH S0 IS  ";D0$
228  PRINT "*"
230  PRINT "*                  SWITCH S1 IS  ";D1$
232  PRINT "*"
234  PRINT "*                  SWITCH S2 IS  ";D2$
236  PRINT "*"
238  PRINT "*                  SWITCH S3 IS  ";D3$
240  PRINT "*"
242  PRINT "*                  SWITCH S4 IS  ";D4$
244  PRINT "*"
246  PRINT "*                  SWITCH S5 IS  ";D5$
248  PRINT "*"
250  PRINT "*********************************************"
299  GOTO 110
```

(dR), relative system error, and sampling frequency (F_s). We will take a look at three examples of A/D converters which are very different in design, using separate and distinct processes to perform the analog-to-digital conversion. I will spend the rest of this section making general comments that will apply to each example, saving specific comments for the individual circuits.

For our purposes, we will define an analog signal as being generally smooth, continuous, and analytical, for example, the output voltage from a pressure transducer, the output voltage from some analytical instrument, or the voltage resulting from some physiological phenomenon such as the electrocardiogram. We shall define a discrete signal as one which is constrained to specific voltage levels, the interval between levels determined by dividing the maximum voltage range (V_{max}) by the number of possible intervals (K). Consequently, any analog voltage which is within the maximum voltage range can be represented as a discrete quantity, the magnitude being equal to some multiple of dR, where dR is defined by Equation 3.1:

$$dR = \frac{V_{max}}{k} \tag{3.1}$$

Resolution

The function of an A/D converter is to transform an analog quantity into a digital quantity which can be handled by a computer. This transformation usually involves sampling the continuous voltage, representing the voltage as a discrete value, and then formating this quantity so that the computer can process it. An example of a signal represented in both continuous and discrete forms is shown in Figure 3.3. In general, we will assume that Y axis values are dependent upon X axis values such that Y can be expressed as some function of X.

$$Y = F(X) \tag{3.2}$$

Resolution, as we will be using the term, is related to our ability to distinguish between two voltages that have magnitudes which are very close together. The smallest magnitude difference we can detect will define the resolution of our system. For each of the analog-to-digital systems we will discuss, resolution will be equal to the magnitude of a unit change in the least significant digit of the output of the converter.

Relative System Error

Accuracy is related to our ability to determine the actual value of an unknown input voltage. Accuracy will be a function of the

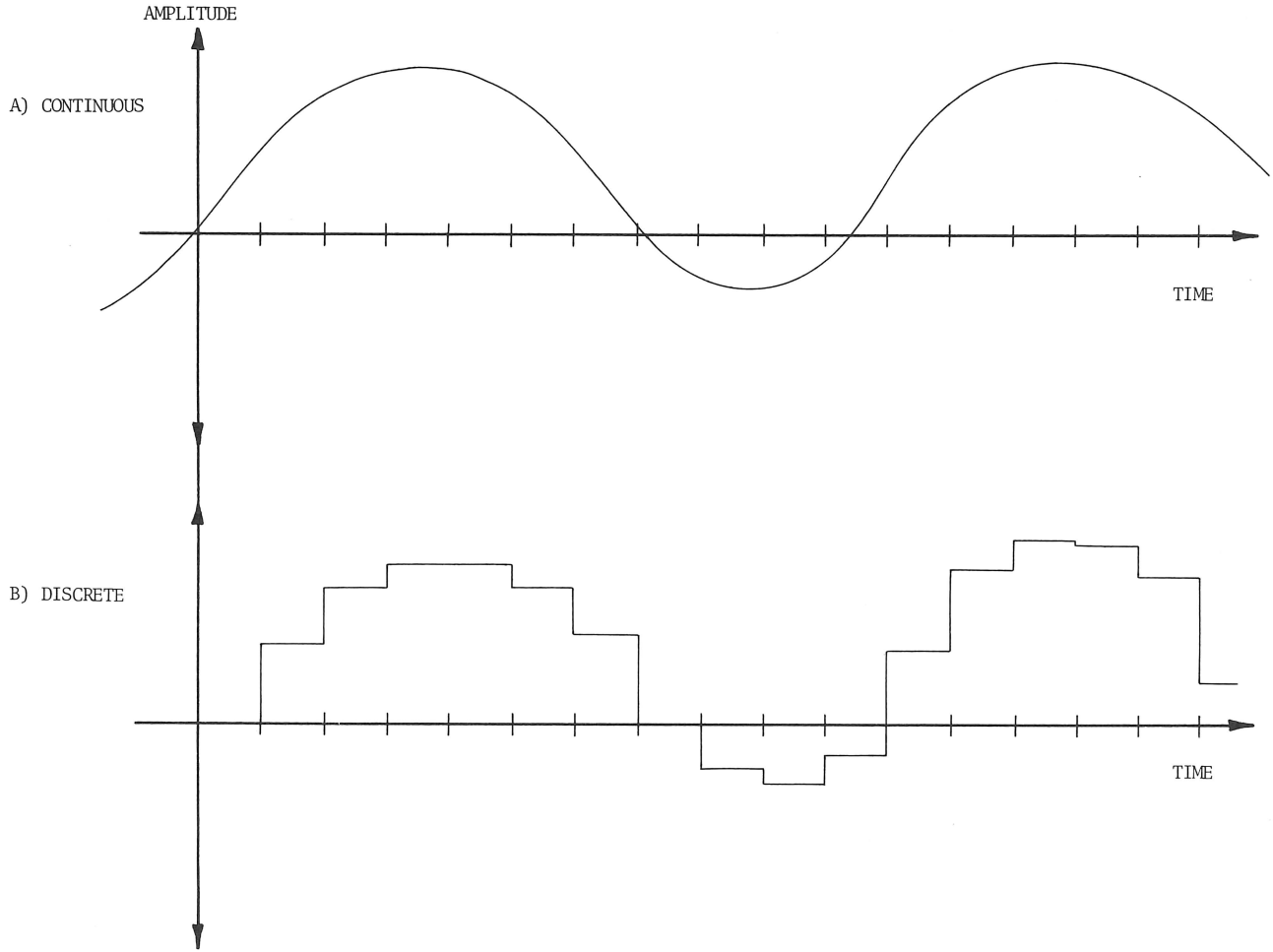


FIGURE 3.3 Continuous and discrete waveforms.

linearity of the system, gain and offset errors, resolution, and magnitude of the signal that we are measuring. In general, the main source of system inaccuracy usually results from the necessity to represent the analog voltage by a discrete quantity. If we assume that this is true for the circuits that we will be building, we can define relative system error as the ratio of system resolution to the magnitude of the voltage being measured. Obviously, for a given system, relative system error will be minimized when the unknown input voltage is equal to the maximum value that the system can handle.

Sampling Theory

Since an A/D converter samples an input signal sequentially with respect to time, the output voltage (Y) can be expressed in the form Y(1), Y(2), and so on. Y(N), where N is equal to the sample number. The rate (F_s) at which we sample the input signal determines the maximum frequency component which can theoretically be detected. The sampling rate can be expressed as a function of the time between samples by the following equation:

$$F_s = 1/dt \text{ samples per second where } dt=[t/N+1)-t(N)] \quad (3.3)$$

The sampling theorum states that we should sample at a rate which is at least twice the frequency (f_c) of the highest significant frequency component that is present in the waveform which we will be digitizing. In practice, the sampling frequency should be ten times F_c to allow you to reconstruct the complex waveform from the digital data without having to be overimaginative. Remember that you can always throw out data points once you have them if you find that you have sampled at a higher rate than was necessary.

In some applications, you might not be interested in the highest frequency component that was contained in the input signal, but only in lower frequency components. Aliasing, impersonation of a low frequency signal by a high frequency signal, results from choosing a sampling rate that is too low for the frequency components that make up the input signal. Figure 3.4 shows how a relatively high frequency signal and a relatively low frequency signal can share identical sample points, thus making it

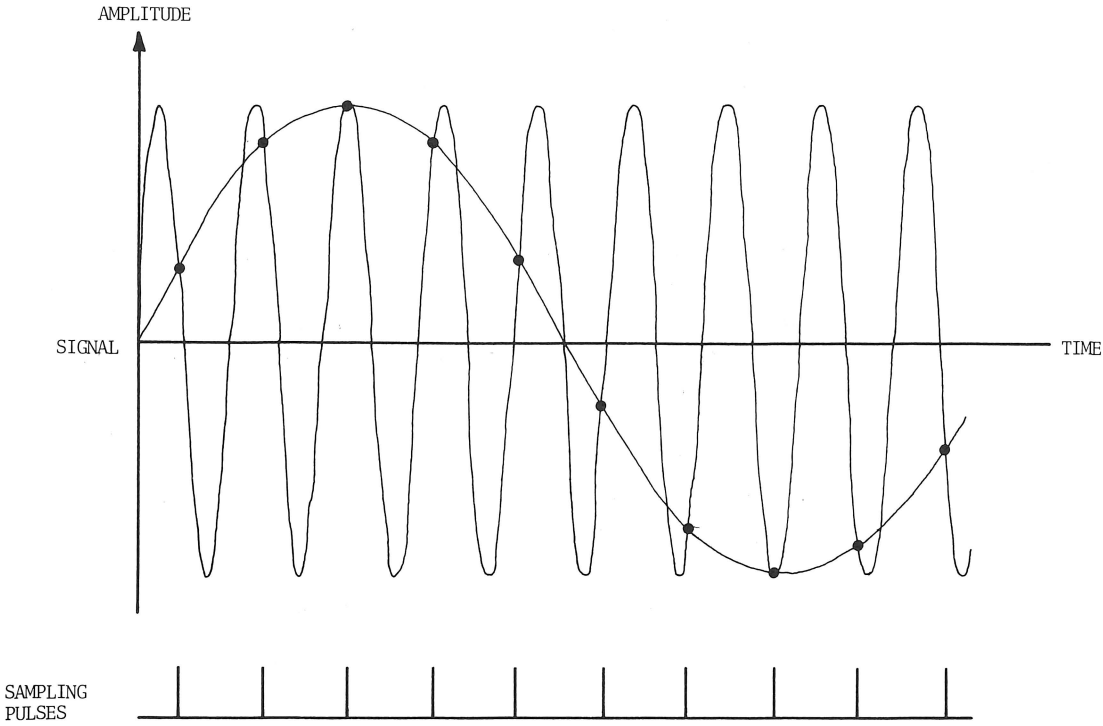


FIGURE 3.4 Aliasing error caused by inadequate sampling rate.

impossible to differentiate between the two signals. For applications where you will be sampling at rates that are less than $2F_c$, you must insert a low pass filter at the input of the A/D converter to limit the frequency content and to ensure faithful reproduction of the input signal.

8-bit, Low-speed A/D Converter

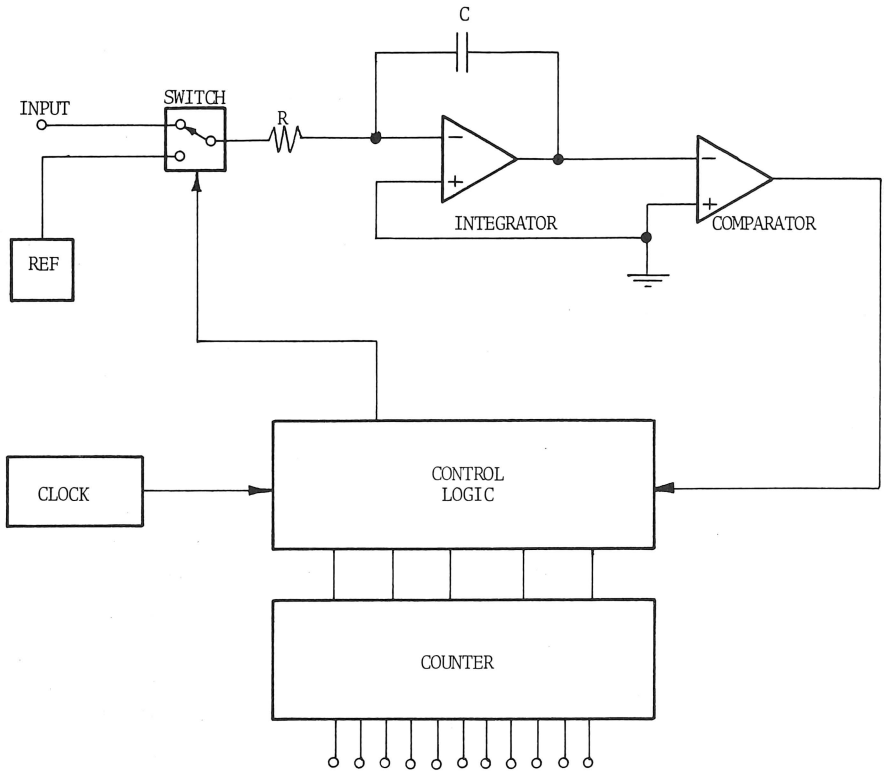
The MC1443 (Motorola Semiconductor Products Inc., Austin, Texas 78721) is a high-performance, low-power, three and one half digit A/D converter combining both linear CMOS and digital CMOS circuitry. This device, when combined with two external resistors and two external capacitors, forms a dual slope A/D converter featuring automatic zero correction and automatic polarity. By using an indirect conversion technique, the dual slope system realizes some of the following positive characteristics:

1. Conversion accuracy is independent of component values and the clock frequency.
2. Differential linearity is excellent.
3. The integration process provides rejection of high-frequency noise and averaging of small voltage changes that may occur during the conversion process.

The main disadvantage to the dual slope technique is that the analog-to-digital conversion process takes a relatively long time, consequently limiting the sampling rate. In spite of this, the device is ideal for digital voltmeters, digital thermometers, and other such devices not requiring sampling rates over 100 samples per second.

Figure 3.5 has been included to help you understand the dual slope conversion process. The actual configuration of the analog circuitry is dependent on the polarity of the input voltage during

FIGURE 3.5 Simplified block diagram for a typical dual slope A/D converter.



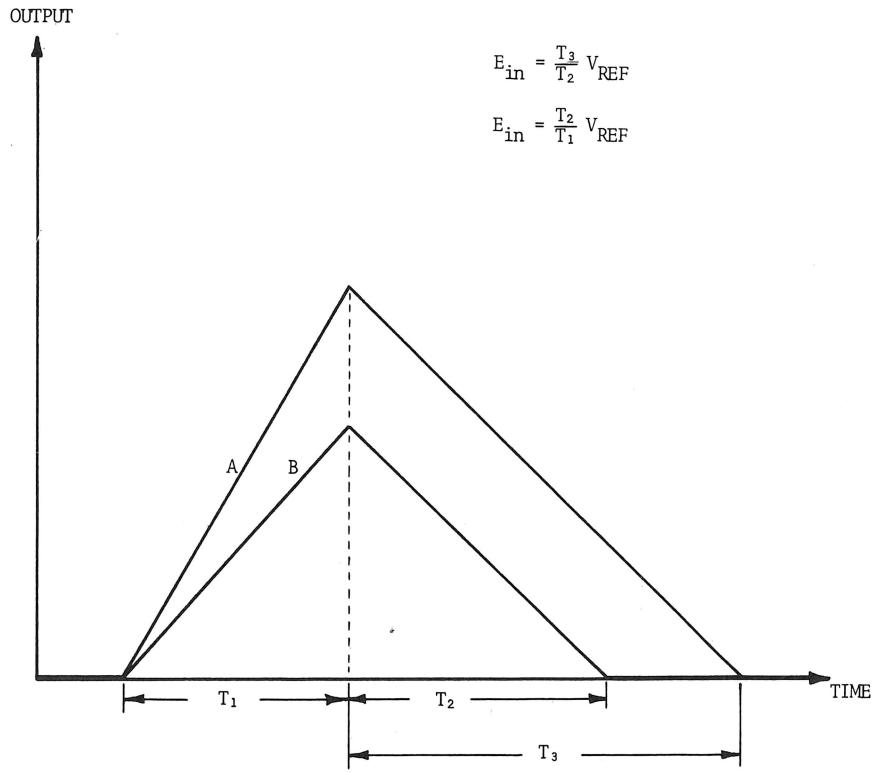


FIGURE 3.6 Integrator output plotted as a function of time for two different input voltages converted by the dual slope process.

the previous conversion cycle, and it is automatically switched by the internal logic circuits. I have chosen to show the analog circuit configuration that would be used when a negative voltage is connected to the input. When performing an A/D conversion, the MC14433 internal control logic first connects the unknown input voltage to the input of an integrator for a fixed period of time determined by an internal clock (See Figure 3.6 for a plot of the integrator output as a function of time.) This results in the voltage across the integrator capacitor increasing to a value which is proportional to the input voltage averaged over the time interval that the input is connected. At the end of this interval, the input to the integrator is switched from the unknown voltage to a reference voltage. The purpose of the reference voltage is to cause the integrator capacitor to discharge at a known rate while a counter

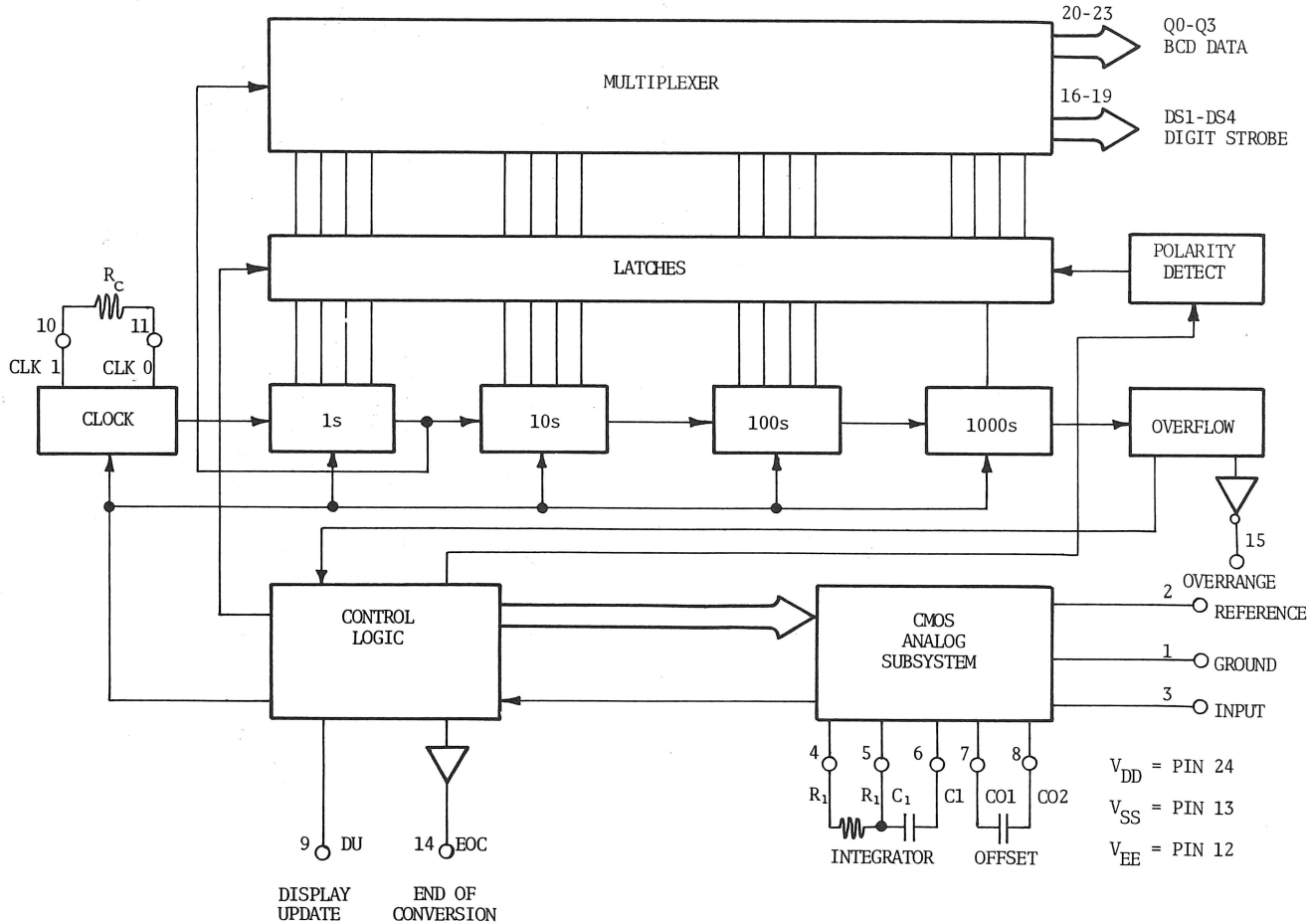
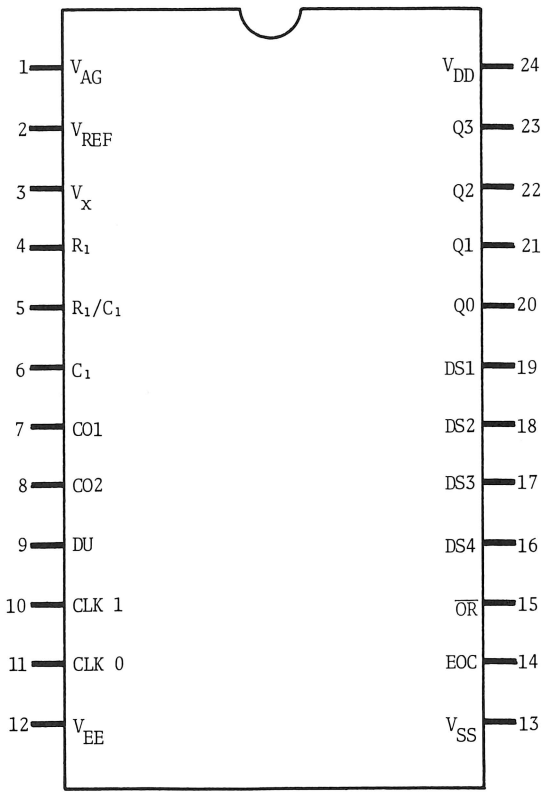


FIGURE 3.7 Block diagram of the Motorola MC 1433 3½ digit A/D converter.

keeps track of the length of time it takes the voltage to return to zero. Note that the count associated with a given input voltage is a function of the reference voltage and the ratio of the time that it takes to charge and discharge the integrator capacitor. In summary, the MC14433 uses a ratiometric measurement scheme that produces an output reading that is a function of the ratio of the unknown input voltage to the reference voltage, where a ratio of 1 equals a count of 1999. It should be obvious to the reader that absolute stability of the reference voltage is necessary to ensure reproducible readings from sample to sample.

Figure 3.7 shows the actual block diagram and Figure 3.8 shows the pin assignment for the MC14433. This integrated circuit operates from standard 5 volt positive (pin 24) and 5 volt negative (pin 12) supplies. (See Appendix C for power supply circuit configurations.) The absolute value of the input voltage

FIGURE 3.8 Pin assignment for the MC14433.



$$V_{out} = \left[\frac{R_2}{R_1 + R_2}\right] V_{in}$$

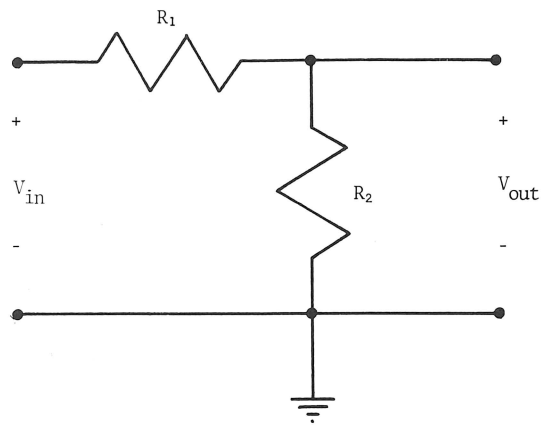
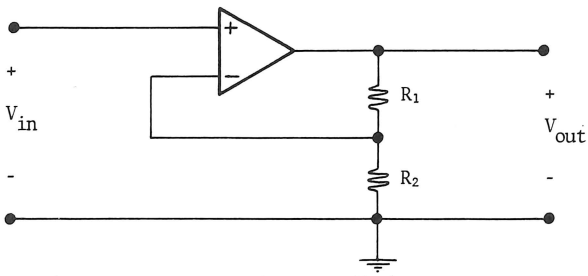


FIGURE 3.9 Simple resistive voltage divider network.

can vary between 0 and 1.999 volts. If the magnitude of the input voltage is greater than the upper limit of 1.999 volts, you can use the voltage divider circuit shown in Figure 3.9 to reduce the voltage to an acceptable value. On the other hand, if the input voltage is less than .2 volts, you will achieve greater accuracy by using a circuit similar to the one shown in Figure 3.10 to increase the magnitude of the input voltage. Appendix B has been in-

FIGURE 3.10 Simple noninverting amplifier.

$$V_{out} = \left[1 + \frac{R_2}{R_1}\right] V_{in}$$



cluded to explain the operation of the amplifier circuits such as the one shown in this figure. The frequency of the internal system clock of the MC14433 is controlled by selection of the resistor connected between pins 10 and 11. Figure 3.11 shows typical values for frequency as a function of resistance, and the following equation relates the conversion rate (samples per second) to the clock frequency:

$$\text{Conversion rate} = \text{Clock frequency}/16{,}400 \qquad (3.4)$$

Normal operation of MC14433 permits the conversion of an analog signal to a digital signal on a continuous basis, but the results of each conversion are transferred to the output latches only when an appropriate logic pulse is applied to the DISPLAY UPDATE (DU) (pin 9) control line. We can control this transfer of data by providing a positive going pulse to the DU line prior to the ramp-down segment of the conversion cycle. The data that are strobed into the output latches will then be equal to the digital quantity that was obtained from the last A/D conversion.

During the time that the conversion is being performed, the status line, END OF CONVERSION (EOC) (pin 14), is low indicating that the converter is busy. Upon completion of the conversion cycle, this line produces a pulse whose width is equal to one half of the period of the system clock. When this output is wired directly back into the DU input, the result of every conversion is strobed into the output latches. I will use the EOC status line to indicate to the computer when a conversion has been completed and, consequently, when new data has been strobed into the output latches.

The result of an analog-to-digital conversion is contained in the internal output latches in a binary format. However, the data are sent to the external world over the data lines (pins 20 to 23) in a multiplexed, binary coded decimal (BCD) format. 8 bits of information are used to transfer the results of a conversion. The four most significant bits (pins 16 to 19) contain the code for a particular digit, and the four least significant bits (pins 20 to 23) contain the binary value of the digit that is selected. The digit select output lines (pins 16 to 19) go high when the respective digit is selected, and the data lines then contain the value of the selected digit. The digit select timing sequence is arranged so that the most

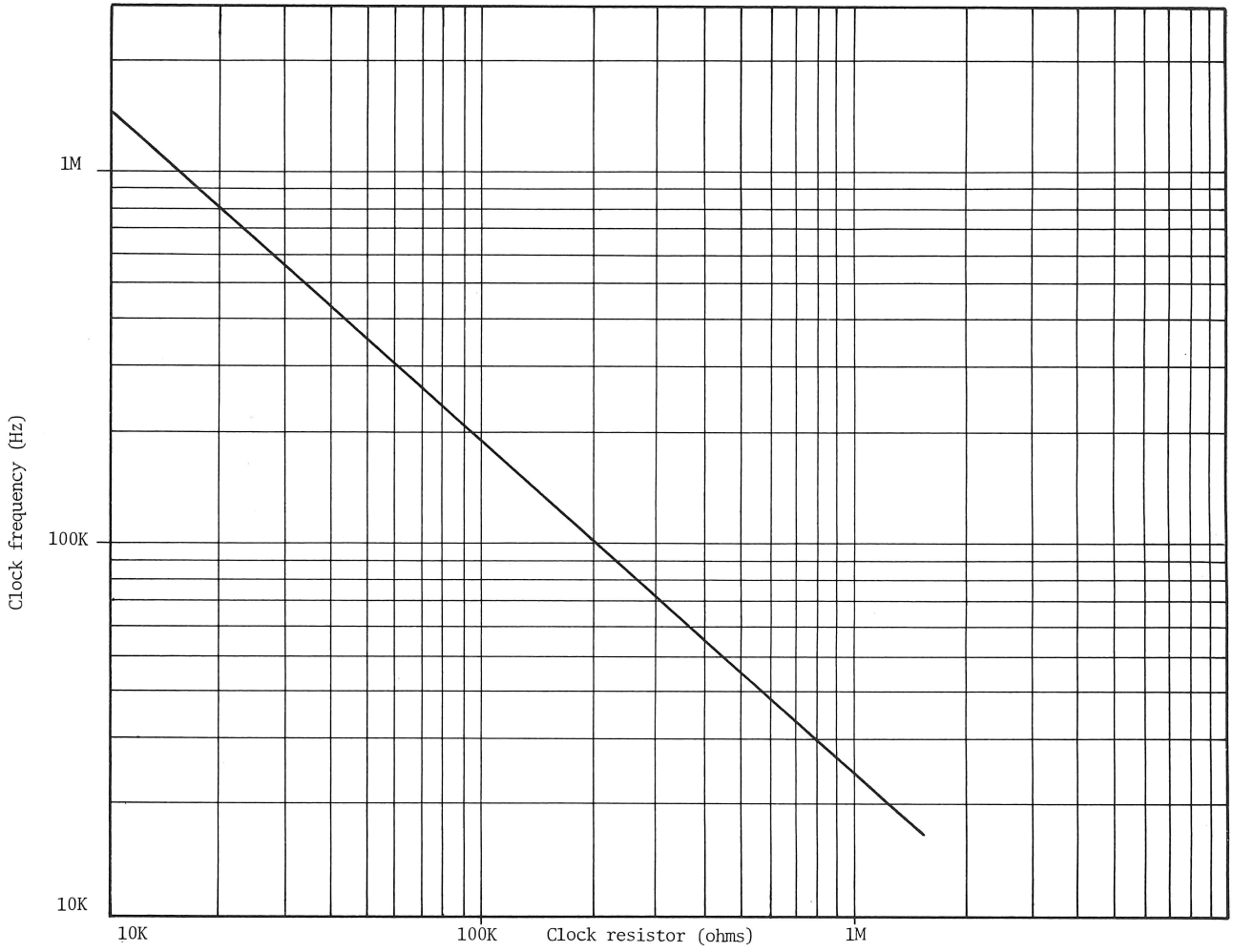


FIGURE 3.11 Typical clock frequency as a function of clock resistor (R_c).

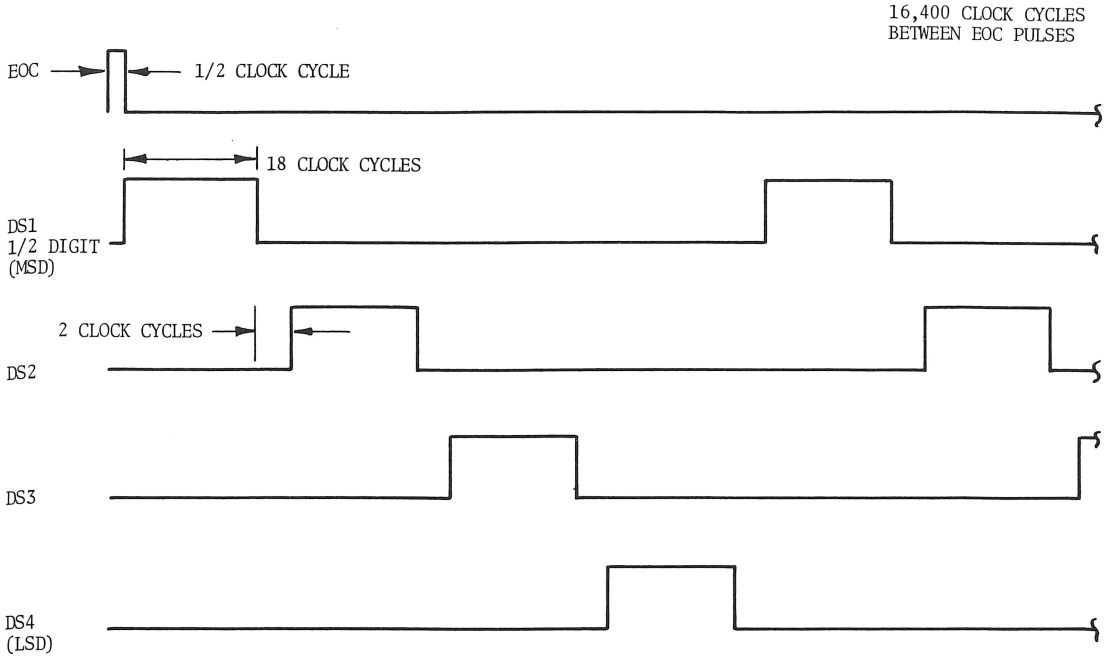


FIGURE 3.12 Digit select timing diagram for the MC14433.

significant digit (MSD) (one half digit) is selected immediately after an EOC pulse. The remaining digits are sequenced as shown in Figure 3.12. When the MSD is multiplexed, the data lines contain not only the value of that digit but also coded information relating to overrange, underrange, and polarity as shown in Table 3.1.

Figure 3.13 shows the low-speed, A/D converter circuit configured for the Apple II. Looking at the upper portion of the figure, you will see the MC14433 A/D converter. The clock resistor (R_c) has been selected and the EOC and DU control lines connected together so that fifteen conversions per second are being performed on a continuous basis. All data and status lines to the Apple II are isolated through the MC14503 three-state buffers (IC7 and IC8). IC4, configured as an R/S flip-flop that is initially reset by the computer, is set by the MC14433 after an alalog-to-digital conversion has been completed. When the Apple II senses this change in status, it starts the decoding and data transfer process. The 6502 processor speed is high enough to enable one conversion to be decoded and stored before another conversion begins. A

TABLE 3.1 Truth table showing the information format on the multiplexed data lines during selection of DS1.

Coded Consition of MSD	Q3	Q2	Q1	Q0	BCD to 6 Segment Decoding
+0	1	1	1	0	Blank
-0	1	0	1	0	Blank
+0 UR	1	1	1	1	Blank
-0 UR	1	0	1	1	Blank
+1	0	1	0	0	4 → 1 Hook up
-1	0	0	0	0	0 → 1 only seg b
+1 OR	0	1	1	1	7 → 1 and c to
-1 OR	0	0	1	1	3 → 1 MCD

Notes for Truth Table

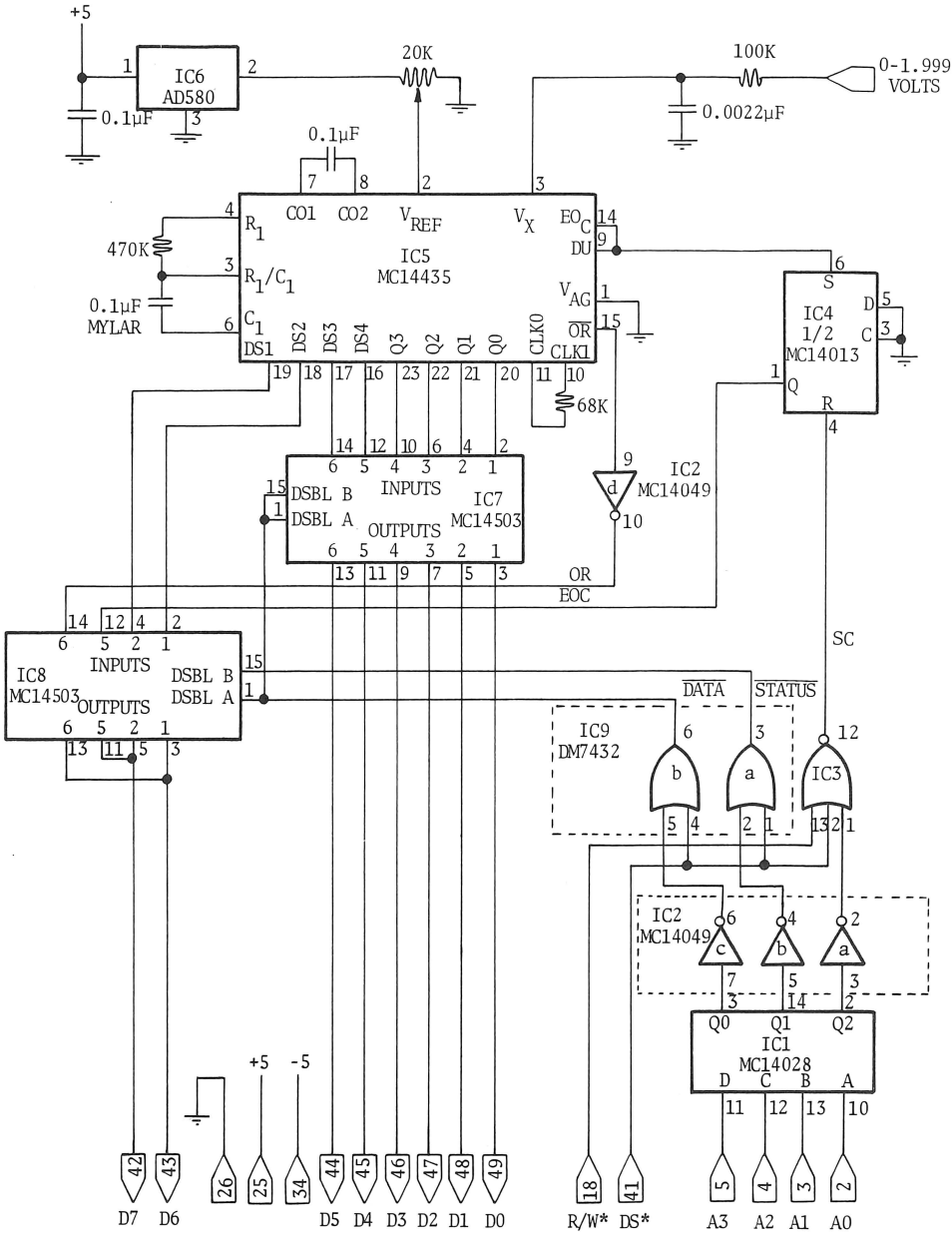
Q3 - 1/2 digit, low for "1", high for "0"
Q2 - Polarity: "1" = positive, "0" = negative
Q0 - Out of range condition exists if Q0 = 1. When used in conjunction with Q3 the type of out of range condition is indicated, i.e., Q3 = 0 → OR or Q3 = 1 → UR.

The overrange indication (Q3 = 0 and Q0 = 1) occurs when the count is greater than 1999, e.g., 1.999V for a reference of 2.000 V. The underrange indication, useful for autoranging circuits, occurs when the count is less than 180, e.g., 0.180 V for a reference of 2.000 V.

stable reference voltage source is obtained from the output of the Analog Devices AD580 voltage regulator (IC6).

The right lower section of Figure 3.13 shows the control logic that is used to coordinate the transfer of signals to and from the computer. The least significant four bits of the address bus are decoded by IC1 and are used for on-board addressing. By executing an STA $C0F2 machine language command, the status control line (SC) is forced high, resetting IC4. Performing an LDA $C0F1 machine language command transfers the end of conversion (EOC) and overrange (OR) status information into the accumulator. Performing an LDA $C0F1 machine language command transfers the digit select code and the BCD value of the selected digit into the accumulator.

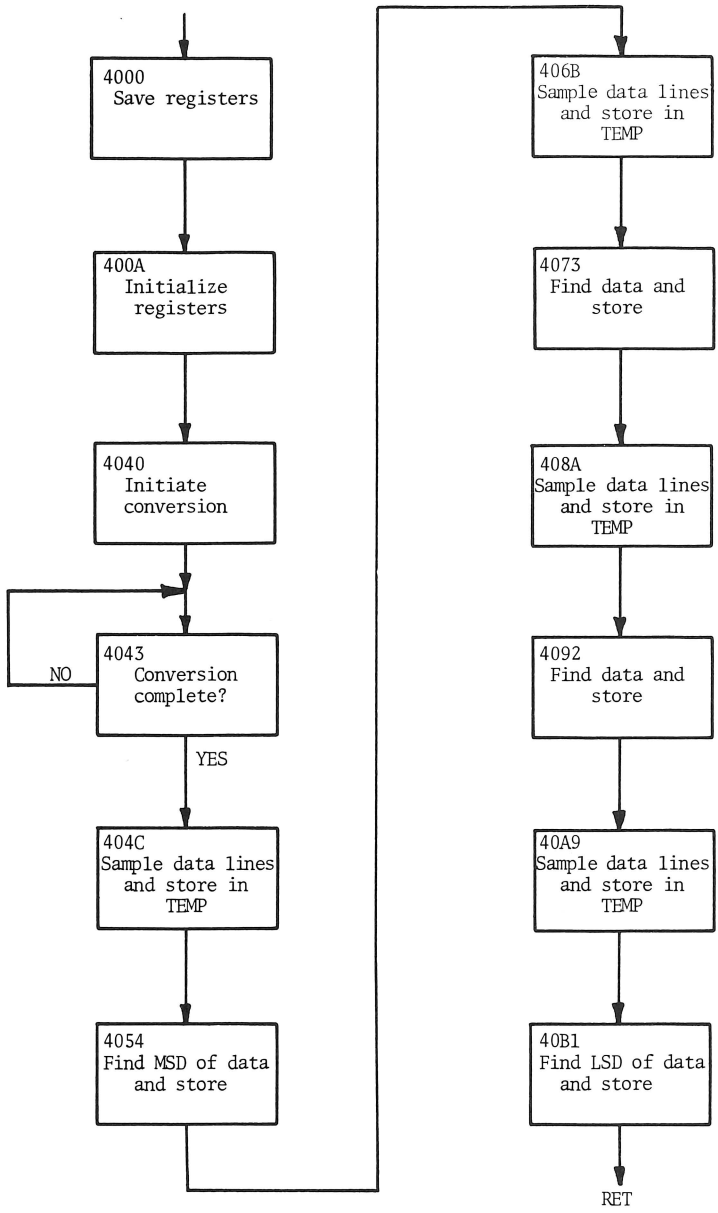
The software portion of the low speed A/D converter has been divided into two parts:



Number	Type	+5	-5	GND
IC1	MC14028	16	--	8
IC2	MC14049	1	--	8
IC3	SN7402	14	--	7
IC4	MC14013	14	--	7
IC5	MC14433	24	12	13
IC6	AD580	1	--	3
IC7	MC14503	16	--	8
IC8	MC14503	16	--	8
IC9	DM7432	14	--	7
IC10	MC14081	14	--	7

FIGURE 3.13 Schematic diagram of the low-speed A/D converter.

FIGURE 3.14 Flow chart for the machine language program 1.



1. A machine language routine was written to control the MC14433, and to provide high-speed transfer of data from the MC14433 to a specific location in computer memory.
2. An Applesoft BASIC program was written to take the data in memory and format it into a voltage that can be displayed as a decimal quantity on the video display.

Figure 3.14 shows the flow chart of the machine language program, and Listing 3.2 shows the coded program with comments. Upon entering the subroutine, the end of the conversion (EOC) flip-flop is reset and the program loops until the MC14433 completes the next conversion and sets the flip-flop. The program then samples the data lines and decides whether or not the most significant digit of data was sampled. If it was not, the program continues to sample the data lines until this digit is obtained. Once this digit is found, it is transferred to memory and the program looks for the second digit. After the four digits representing the digitized input voltage have been stored, the program executes an *RTS* and returns to the BASIC program.

LISTING 3.2 Machine language program for the low-speed A/D converter (single sample).

```
4000   8D B0 49     STA  $49B0    SAVE REGISTERS
4003   8E B1 49     STX  $49B1
4006   8C B2 49     STY  $49B2
4009   08           PHP           SAVE PROC STATUS
400A   A2 00        LDX  #$00     CLEAR X REGISTER
400C   A9 00        LDA  #$00     CLEAR A REGISTER
400E   85 0A        STA  $0A      START LOCATION FOR DATA
4010   A9 4A        LDA  #$4A
4012   85 0B        STA  $0B
4014   4C 40 40     JMP  $4040    JUMP TO TAKE DATA
4017   00           BRK
4018   00           BRK
4019   00           BRK
401A   00           BRK
401B   00           BRK
401C   00           BRK
401D   00           BRK
401E   00           BRK
401F   00           BRK
4020   00           BRK
4021   00           BRK
4022   00           BRK
4023   00           BRK
4024   00           BRK
4025   AD B0 49     LDA  $49B0    RESTORE REGISTERS
4028   AE B1 49     LDX  $49B1
402B   AC B2 49     LDY  $49B2
402E   28           PLP           RESTORE PROC STATUS
402F   60           RTS           RETURN TO BASIC
4030   EA           NOP
```

LISTING 3.2 (*Continued*)

```
4031   EA          NOP
4032   EA          NOP
4033   EA          NOP
4034   EA          NOP
4035   EA          NOP
4036   EA          NOP
4037   EA          NOP
4038   EA          NOP
4039   EA          NOP
403A   EA          NOP
403B   EA          NOP
403C   EA          NOP
403D   EA          NOP
403E   EA          NOP
403F   EA          NOP
4040   8D F2 C0    STA  $C0F2    START CONVERSION
4043   AD F1 C0    LDA  $C0F1    TEST FOR EOC
4046   29 80       AND  #$80
4048   C9 80       CMP  #$80
404A   D0 F7       BNE  $4043    JUMP IF EOC*
404C   AD F0 C0    LDA  $C0F0    INPUT DATA
404F   8D A2 49    STA  $49A2    STORE TEMP
4052   29 80       AND  #$80     CHECK FOR MSD
4054   C9 80       CMP  #$80
4056   D0 F4       BNE  $404C    JUMP IF NOT MSD
4058   AD A2 49    LDA  $49A2    GET DATA
405B   29 0F       AND  #$0F     SAVE 4 BITS
405D   81 0A       STA  ($0A,X)  STORE DATA
405F   4A 0A       LDY  $0A
4061   C8          INY           INCREMENT STORAGE
4062   84 0A       STY  $0A
4064   D0 05       BNE  $406B
4066   A4 0B       LDY  $0B      INCREMENT STORAGE
4068   C8          INY
4069   84 0B       STY  $0B
406B   AD F0 C0    LDA  $C0F0
406E   8D A2 49    STA  $49A2
4071   29 40       AND  #$40     TEST FOR NEXT BYTE
4073   C9 40       CMP  #$40
4075   D0 F4       BNE  $406B    JUMP IF NOT
4077   AD A2 49    LDA  $49A2
407A   29 0F       AND  #$0F
407C   81 0A       STA  ($0A,X)
407E   A4 0A       LDY  $0A
4080   C8          INY
4081   84 0A       STY  $0A
4083   D0 05       BNE  $408A
4085   A4 0B       LDY  $0B
4087   C8          INY
4088   84 0B       STY  $0B
408A   AD F0 C0    LDA  $C0F0
408D   8D A2 49    STA  $49A2
4090   29 20       AND  #$20     TEST FOR NEXT DIGIT
4092   C9 20       CMP  #$20
4094   D0 F4       BNE  $408A
4096   AD A2 49    LDA  $49A2
4099   29 0F       AND  #$0F
409B   81 0A       STA  ($0A,X)
409D   A4 0A       LDY  $0A
409F   C8          INY
40A0   84 0A       STY  $0A
40A2   D0 05       BNE  $40A9
40A4   A4 0B       LDY  $0B
40A6   C8          INY
```

```
40A7   84 0B        STY  $0B
40A9   AD F0 C0     LDA  $C0F0
40AC   8D A2 49     STA  $49A2
40AF   29 10        AND  #$10      TEST FOR NEXT DIGIT
40B1   C9 10        CMP  #$10
40B3   D0 F4        BNE  $40A9
40B5   AD A2 49     LDA  $49A2
40B8   29 0F        AND  #$0F
40BA   81 0A        STA  ($0A,X)
40BC   A4 0A        LDY  $0A
40BE   C8           INY
40BF   84 0A        STY  $0A
40C1   D0 05        BNE  $40C8
40C3   A4 0B        LDY  $0B
40C5   C8           INY
40C6   84 0B        STY  $0B
40C8   4C 25 40     JMP  $4025
```

The BASIC routine has the task of calling the machine language routine and assembling the four digits from each conversion back into a single number which is equal to the measured voltage. This program has been written using the CALL command to jump to the machine language routine. A flow chart for the BASIC program is shown in Figure 3.15 and Listing 3.3 shows the coded program. Listing 3.3 has the machine language program included in it as a series of DATA statements that are read in by line 22. You only have to load the BASIC program to get the A/D converter to work. This program performs A/D conversions on a continuous basis, displaying the value of the analog input voltage on the video monitor.

Once the circuitry has been built, you still have the job of finding any errors that may have been made during construction. To assist you in this process, I am including the following checks for you to make:

1. The voltage at pin 2 on IC5 should be set to 2.00 volts.
2. Using an oscilloscope attached to pin 10 on IC5, you should see a 150,000 Hz distorted square wave varying between +2 and − 2 volts.
3. The voltage at pin 1 on IC4 should be equal to +5 volts. Run the following program to repeatedly reset the flip-flop.

   ```
   100 POKE −16142,0
   110 FOR I=1 TO 20
   120 NEXT I
   130 GOTO 100
   ```
4. After you have loaded the BASIC program, connect a 1.5 volt battery to the input and execute the program. You should see a

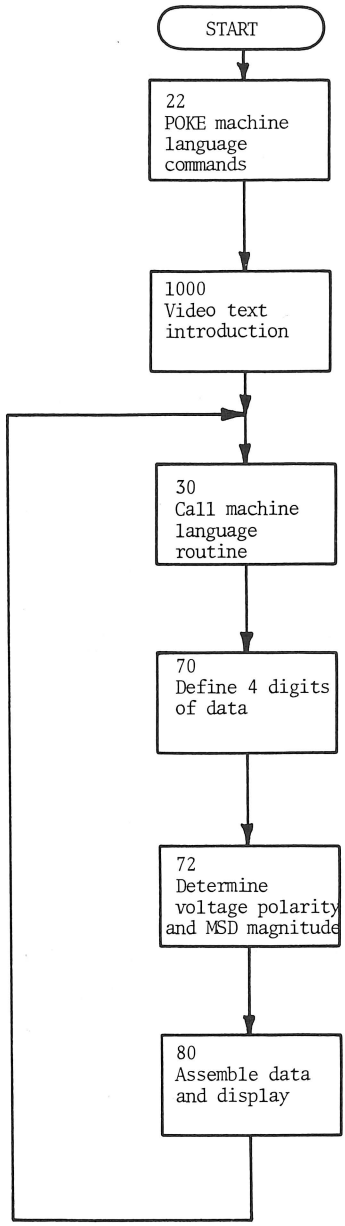


FIGURE 3.15 Flow chart for the BASIC program 1.

LISTING 3.3 BASIC program for the low-speed A/D converter (single sample).

```
10 REM LOW SPEED A/D CONVERTER #1
20 REM R. HALLGREN, APPLE II, 10/27/81
22 FOR I=16384 TO 16586: READ D:POKE I,D:NEXT I
24 GOSUB 1000
26 FOR I=1 TO 255
30 REM CONVERT ONE SAMPLE
50 CALL 16384
70 X4=PEEK(18944):X3=PEEK(18945)
72 X2=PEEK(18946):X1=PEEK(18947)
73 W4=X4
74 IF X4>7 THEN X4=0
75 IF X4=0 THEN GOTO 80
76 X4=1
80 X$=STR$(X4)+STR$(X3)+STR$(X2)+STR$(X1)
81 X=-VAL(X$)/1000
82 IF X4=0 THEN W4=W4-8
83 IF W4>3 THEN X=-X
84 HOME
86 VTAB 12
88 PRINT "THEN INPUT VOLTAGE EQUALS ";X;" VOLTS"
90 NEXT I
99 END
1000 REM INTRODUCTION
1010 HOME
1020 PRINT "THIS IS A DEMONSTRATION PROGRAM FOR THE"
1022 PRINT "";""
1040 PRINT "LOW SPEED A/D CONVERTER. THE INPUT"
1042 PRINT "";""
1050 PRINT "VOLTAGE SHOULD BE LESS THAN 1.999 VOLTS"
1052 PRINT "";""
1060 PRINT "AND GREATER THAN 0 VOLTS."
1062 PRINT "";""
1070 PRINT "PRESS THE SPACE BAR TO CONTINUE."
1072 PRINT "";""
1080 GET K$
1082 IF K$<>" " THEN GOTO 1080
1090 RETURN
2000 DATA 141,176,73,142,177,73,140,178,73,8,162,0,169,0,
        133
2002 DATA 10,169,74,133,11,76,64,64,0,0,0,0,0,0,0,0,0,0,0
2004 DATA 0,0,173,176,73,174,177,73,172,178,73,40,96
2006 DATA 234,234,234,234,234,234,234,234,234,234,234
2008 DATA 234,234,234,234,234,141,242,192,173,241,192
2010 DATA 41,128,201,128,208,247,173,240,192,141,162
2011 DATA 73,41,128,201,128,208,244,173
2012 DATA 162,73,41,15,129,10,164,10,200,132,10,208
2014 DATA 5,164,11,200,132,11,173,240,192,141,162,73
2016 DATA 41,64,201,64,208,244,173,162,73,41,15,129
2018 DATA 10,164,10,200,132,10,208,5,164,11,200,132
2020 DATA 11,173,240,192,141,162,73,41,32,201,32
2022 DATA 208,244,173,162,73,41,15,129,10,164,10
2024 DATA 200,132,10,208,5,164,11,200,132,11,173
2026 DATA 240,192,141,162,73,41,16,201,16,208,244
2028 DATA 173,162,73,41,15,129,10,164,10,200,132
2030 DATA 10,208,5,164,11,200,132,11,76,37,64
```

video introduction and, after pressing the space bar, you should see the value of the battery voltage (1.54 volts) displayed on the CRT.

The MC14433 circuitry has been set up so that it is performing an analog-to-digital conversion approximately every .067 sec-

onds (fifteen samples per second). Listing 3.4 shows a machine language program that takes a total of 256 samples before returning to the calling routine. Figure 3.16 shows a flow chart for the program. Listing 3.5 shows a BASIC program which calls the machine language routine and then plots the data. Figure 3.17 shows a flow chart for the BASIC program. The BASIC program has the machine language program included in it as a series of DATA statements that are read in by line 24.

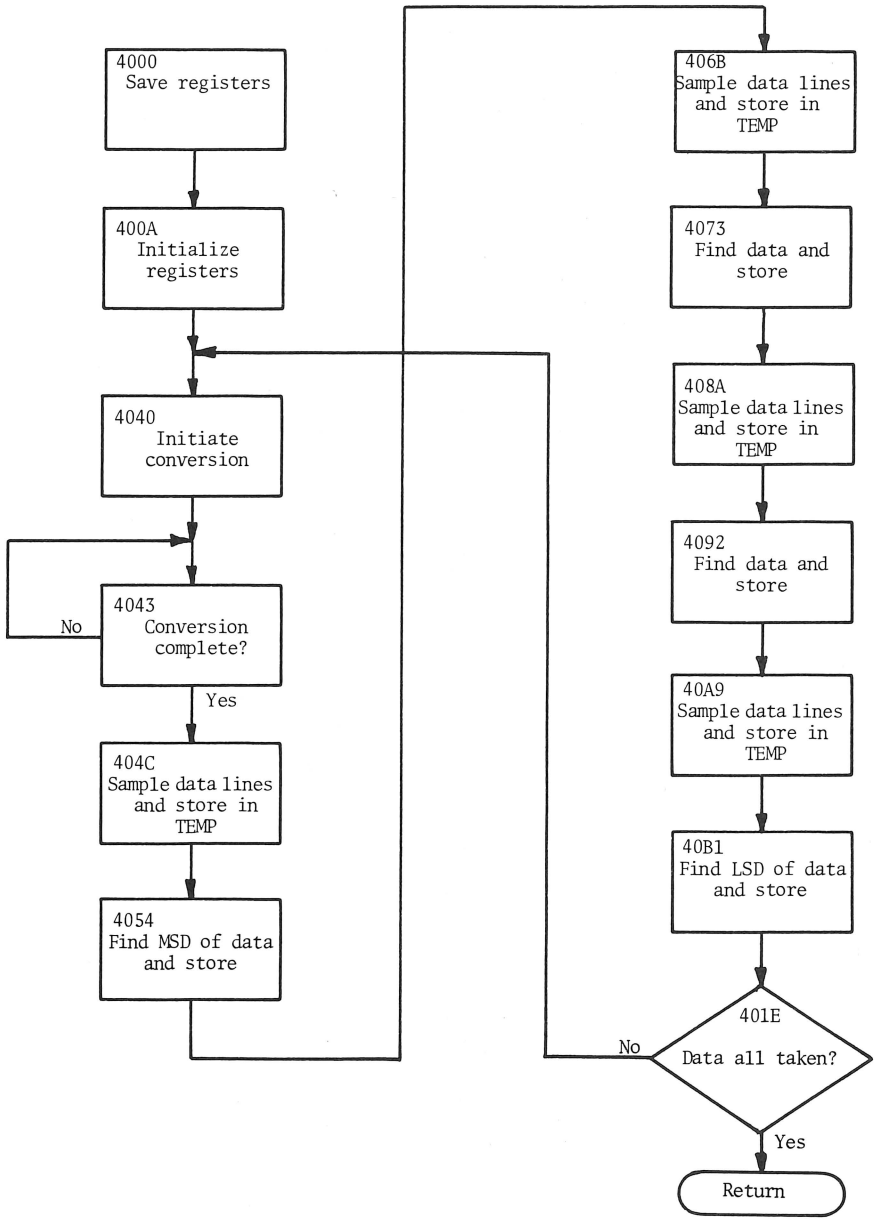
Hooking the 1.5 volt battery to the input should give a straight line plot. Figure 3.18 shows a simple resistor, capacitor, and battery combination which can be used to demonstrate the capability of the system. Initially, disconnect the battery and connect the input of the A/D converter across the capacitor. Begin

LISTING 3.4 Machine language program for the low-speed A/D converter (256 samples).

```
4000   8D B0 49     STA  $49B0    SAVE REGISTERS
4003   8E B1 49     STX  $49B1
4006   8C B2 49     STY  $49B2
4009   08           PHP           SAVE PROC STATUS
400A   A2 00        LDX  #$00     CLEAR X REGISTER
400C   A9 00        LDA  #$00     CLEAR A REGISTER
400E   85 0A        STA  $0A      START LOCATION FOR DATA
4010   A9 4A        LDA  #$4A
4012   85 0B        STA  $0B
4014   A9 00        LDA  #$00     STOP LOCATION FOR DATA
4016   8D A0 49     STA  $49A0
4019   A9 4E        LDA  #$4E
401B   8D A1 49     STA  $49A1
401E   AD A1 49     LDA  $49A1
4021   C5 0B        CMP  $0B
4023   D0 1B        BNE  $4040
4025   AD B0 49     LDA  $49B0    RESTORE REGISTERS
4028   AE B1 49     LDX  $49B1
402B   AC B2 49     LDY  $49B2
402E   28           PLP           RESTORE PROC STATUS
402F   60           RTS           RETURN TO BASIC
4030   EA           NOP
4031   EA           NOP
4032   EA           NOP
4033   EA           NOP
4034   EA           NOP
4035   EA           NOP
4036   EA           NOP
4037   EA           NOP
4038   EA           NOP
4039   EA           NOP
403A   EA           NOP
403B   EA           NOP
403C   EA           NOP
403D   EA           NOP
403E   EA           NOP
403F   EA           NOP
4040   8D F2 C0     STA  $C0F2    START CONVERSION
```

```
4043   AD F1 C0     LDA  $C0F1    TEST FOR EOC
4046   29 80        AND  #$80
4048   C9 80        CMP  #$80
404A   D0 F7        BNE  $4043    JUMP IF EOC*
404C   AD F0 C0     LDA  $C0F0    INPUT DATA
404F   8D A2 49     STA  $49A2    STORE TEMP
4052   29 80        AND  #$80     CHECK FOR MSD
4054   C9 80        CMP  #$80
4056   D0 F4        BNE  $404C    JUMP IF NOT MSD
4058   AD A2 49     LDA  $49A2    GET DATA
405B   29 0F        AND  #$0F     SAVE 4 BITS
405D   81 0A        STA  ($0A,X)  STORE DATA
405F   4A 0A        LDY  $0A
4061   C8           INY           INCREMENT STORAGE
4062   84 0A        STY  $0A
4064   D0 05        BNE  $406B
4066   A4 0B        LDY  $0B      INCREMENT STORAGE
4068   C8           INY
4069   84 0B        STY  $0B
406B   AD F0 C0     LDA  $C0F0
406E   8D A2 49     STA  $49A2
4071   29 40        AND  #$40     TEST FOR NEXT BYTE
4073   C9 40        CMP  #$40
4075   D0 F4        BNE  $406B    JUMP IF NOT
4077   AD A2 49     LDA  $49A2
407A   29 0F        AND  #$0F
407C   81 0A        STA  ($0A,X)
407E   A4 0A        LDY  $0A
4080   C8           INY
4081   84 0A        STY  $0A
4083   D0 05        BNE  $408A
4085   A4 0B        LDY  $0B
4087   C8           INY
4088   84 0B        STY  $0B
408A   AD F0 C0     LDA  $C0F0
408D   8D A2 49     STA  $49A2
4090   29 20        AND  #$20     TEST FOR NEXT DIGIT
4092   C9 20        CMP  #$20
4094   D0 F4        BNE  $408A
4096   AD A2 49     LDA  $49A2
4099   29 0F        AND  #$0F
409B   81 0A        STA  ($0A,X)
409D   A4 0A        LDY  $0A
409F   C8           INY
40A0   84 0A        STY  $0A
40A2   D0 05        BNE  $40A9
40A4   A4 0B        LDY  $0B
40A6   C8           INY
40A7   84 0B        STY  $0B
40A9   AD F0 C0     LDA  $C0F0
40AC   8D A2 49     STA  $49A2
40AF   29 10        AND  #$10     TEST FOR NEXT DIGIT
40B1   C9 10        CMP  #$10
40B3   D0 F4        BNE  $40A9
40B5   AD A2 49     LDA  $49A2
40B8   29 0F        AND  #$0F
40BA   81 0A        STA  ($0A,X)
40BC   A4 0A        LDY  $0A
40BE   C8           INY
40BF   84 0A        STY  $0A
40C1   D0 05        BNE  $40C8
40C3   A4 0B        LDY  $0B
40C5   C8           INY
40C6   84 0B        STY  $0B
40C8   4C 1E 40     JMP  $401E
```

FIGURE 3.16 Flow chart for the machine language program 2.



LISTING 3.5 BASIC program for digitizing and plotting data.

```
10 REM LOWSPEED A/D CONVERTER
12 REM APPLE II, R. HALLGREN, 10/28/81
24 FOR I=16384 TO 16586:READ D:POKE I,D:NEXT I
104 DIM Z(300):HOME:GOTO 1000
110 CALL 16384
111 HOME:VTAB 24
112 PRINT "THE DIGITIZED DATA IS BEING FORMATTED"
113 PRINT "FOR PLOTTING."
114 X=18944
115 FOR J=0 TO 255
120 V1=PEEK(X):V2=PEEK(X+1)
126 V3=PEEK(X+2):V4=PEEK(X+3)
128 X=X+4
130 IF V1>7 THEN V1=0
132 IF V1=0 THEN GOTO 140
134 V1=1
140 V$=SRT$(V1)+STR$(V2)+STR$(V3)+STR$(V4)
150 Z(J)=VAL(V$)/1000
160 NEXT J
200 HGR:HCOLOR=3
202 HPLOT 20,0 TO 20,150:HPLOT TO 279,150
208 HPLOT 18,0 TO 22,0
210 HPLOT 18,10 TO 22,10
212 HPLOT 18,20 TO 22,20
214 HPLOT 18,30 TO 22,30
216 HPLOT 18,40 TO 22,40
218 HPLOT 18,50 TO 22,50
220 HPLOT 18,60 TO 22,60
222 HPLOT 18,70 TO 22,70
224 HPLOT 18,80 TO 22,80
226 HPLOT 18,90 TO 22,90
228 HPLOT 18,100 TO 22,100
230 HPLOT 18,110 TO 22,110
232 HPLOT 18,120 TO 22,120
234 HPLOT 18,130 TO 22,130
236 HPLOT 18,140 TO 22,140
238 HPLOT 18,150 TO 22,150
240 HPLOT 4,47 TO 4,53:HPLOT 7,53
246 HPLOT 10,47 TO 10,53
248 HPLOT TO 14,53
250 HPLOT TO 14,47:HPLOT TO 10,47:HPLOT TO 7,103
262 HPLOT 14,97 TO 10,97:HPLOT TO 10,100:HPLOT TO 14,100
264 HPLOT TO 14,103:HPLOT TO 10,103
272 HPLOT 14,147 TO 10,147:HPLOT TO 10,153:HPLOT TO 14,153
274 HPLOT TO 14,147
280 HPLOT 30,148 TO 30,152
281 HPLOT 40,148 TO 40,152:HPLOT 50,148 TO 50,152
282 HPLOT 60,148 TO 60,152:HPLOT 70,148 TO 70,152
283 HPLOT 80,148 TO 80,152:HPLOT 90,148 TO 90,152
284 HPLOT 100,148 TO 100,152:HPLOT 110,148 TO 110,152
285 HPLOT 120,148 TO 120,152:HPLOT 130,148 TO 130,152
286 HPLOT 140,148 TO 140,152:HPLOT 150,148 TO 150,152
287 HPLOT 160,148 TO 160,152:HPLOT 170,148 TO 170,152
288 HPLOT 180,148 TO 180,152:HPLOT 190,148 TO 190,152
289 HPLOT 200,148 TO 200,152:HPLOT 210,148 TO 210,152
290 HPLOT 220,148 TO 220,152:HPLOT 230,148 TO 230,152
291 HPLOT 240,148 TO 240,152:HPLOT 250,148 TO 250,152
292 HPLOT 260,148 TO 260,152:HPLOT 270,148 TO 270,152
300 FOR J=0 TO 255
310 HPLOT J+20,150-(Z(J)*100)
320 NEXT J
999 END
1000 PRINT "PRESS 'RETURN' TO START A/D"
1010 K=PEEK(-16384)
```

LISTING 3.5 (*Continued*)

```
1012 POKE -16368,0
1014 IF K>127 THEN GOTO 1020
1016 GOTO 1010
1020 TEXT
1022 HOME
1024 VTAB 24
1026 PRINT "256 DATA POINTS ARE BEING DIGITIZED"
1028 GOTO 110
1099 END
2000 DATA 141,176,73,142,177,73,140,178,73,8,162,0,169,0,
          133
2002 DATA 10,169,74,133,11,169,0,141,160,73,169,78,141,
          161,73
2004 DATA 173,161,73,197,11,208,27,173,176,73,174,177,73,
          172
2006 DATA 178,73,40,96,234,234,234,234,234,234,234,234,234
2008 DATA 234,234,234,234,234,234,234,141,242,192,173,241,
          192
2010 DATA 41,128,201,128,208,247,173,240,192,141,162,73,41,
          128
2012 DATA 201,128,208,244,173,162,73,41,15,129,10,164,10,
          200
2014 DATA 132,10,208,5,164,11,200,132,11,173,240,192,141,
          162
2016 DATA 73,41,64,201,64,208,244,173,162,73,41,15,129,10,
          164
2018 DATA 10,200,132,10,208,5,164,11,200,132,11,173,240,
          192,141
2020 DATA 162,73,41,32,201,32,208,244,173,162,73,41,15,
          129,10
2022 DATA 164,10,200,132,10,208,5,164,11,200,132,11,173,
          240
2024 DATA 192,141,162,73,41,201,16,208,244,173,162,73,41
2026 DATA 15,129,10,164,10,200,132,10,208,5,164,11,200
2028 DATA 132,11,76,30,64
```

executing the program. Connect the battery to the circuit. The plot (See Figure 3.19) should show an exponential rise in voltage across the capacitor—exactly what you would expect. Figure 3.20 shows the plot of a .1 Hz sine wave digitized at a sampling rate of fifteen samples per second.

Ten-bit, High-speed A/D Converter

The AD571 (Analog Devices, Norwood, Massachusetts 02062) is a ten-bit, successive-approximation, A/D converter consisting of an internal D/A converter, voltage reference, clock, comparator, approximation register, and output buffers. With this device, an analog voltage can be converted into a quantity represented by 10 binary bits in approximately 25 microseconds, conversion rate not being a function of the magnitude of the input voltage. Figure 3.21 shows the block diagram and pin assignment for the AD571. This integrated circuit can operate from a positive supply voltage

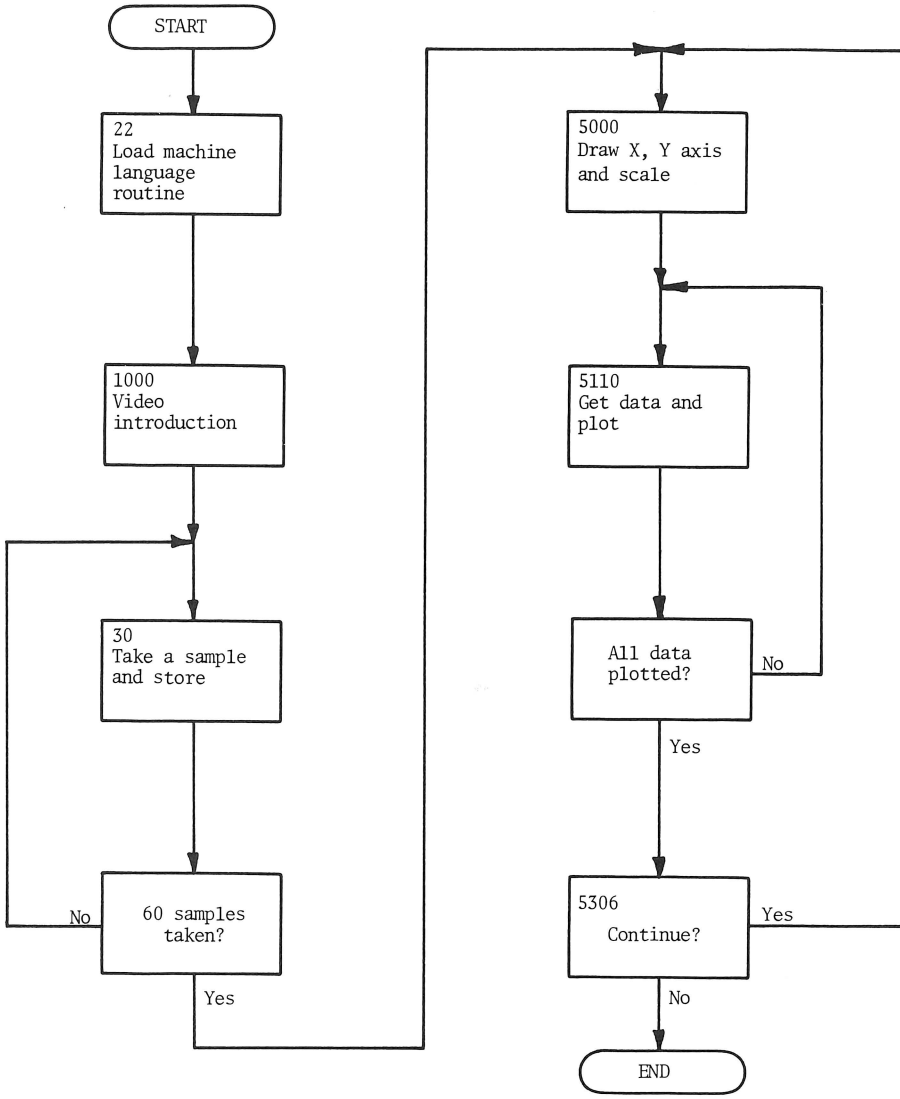
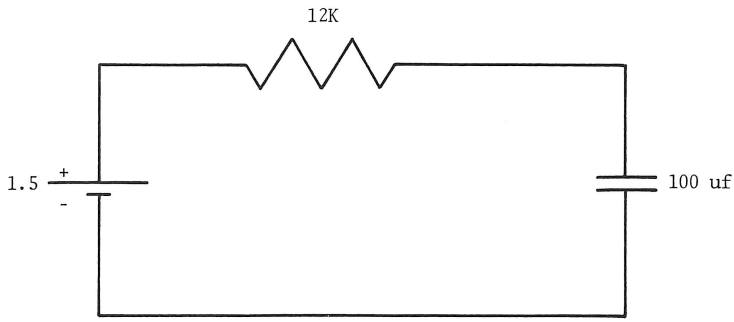


FIGURE 3.17 Flow chart for the BASIC program 2.

FIGURE 3.18 Series RC circuit for low-speed A/D converter demonstration.



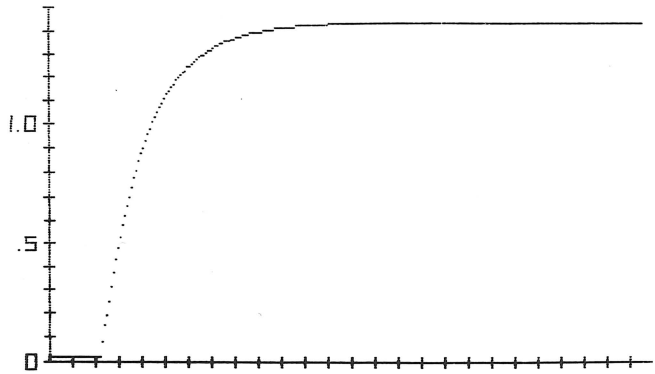


FIGURE 3.19 Voltage across the capacitor measured as a function of time.

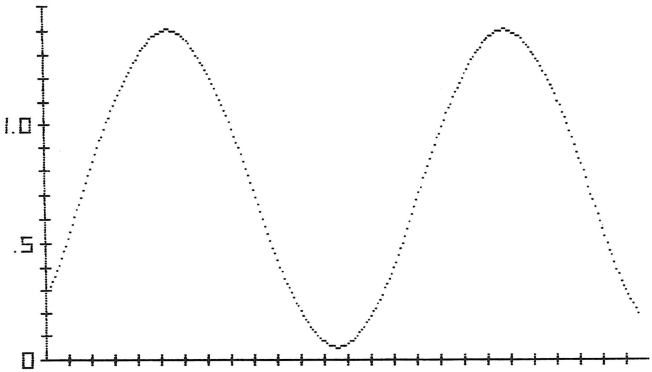
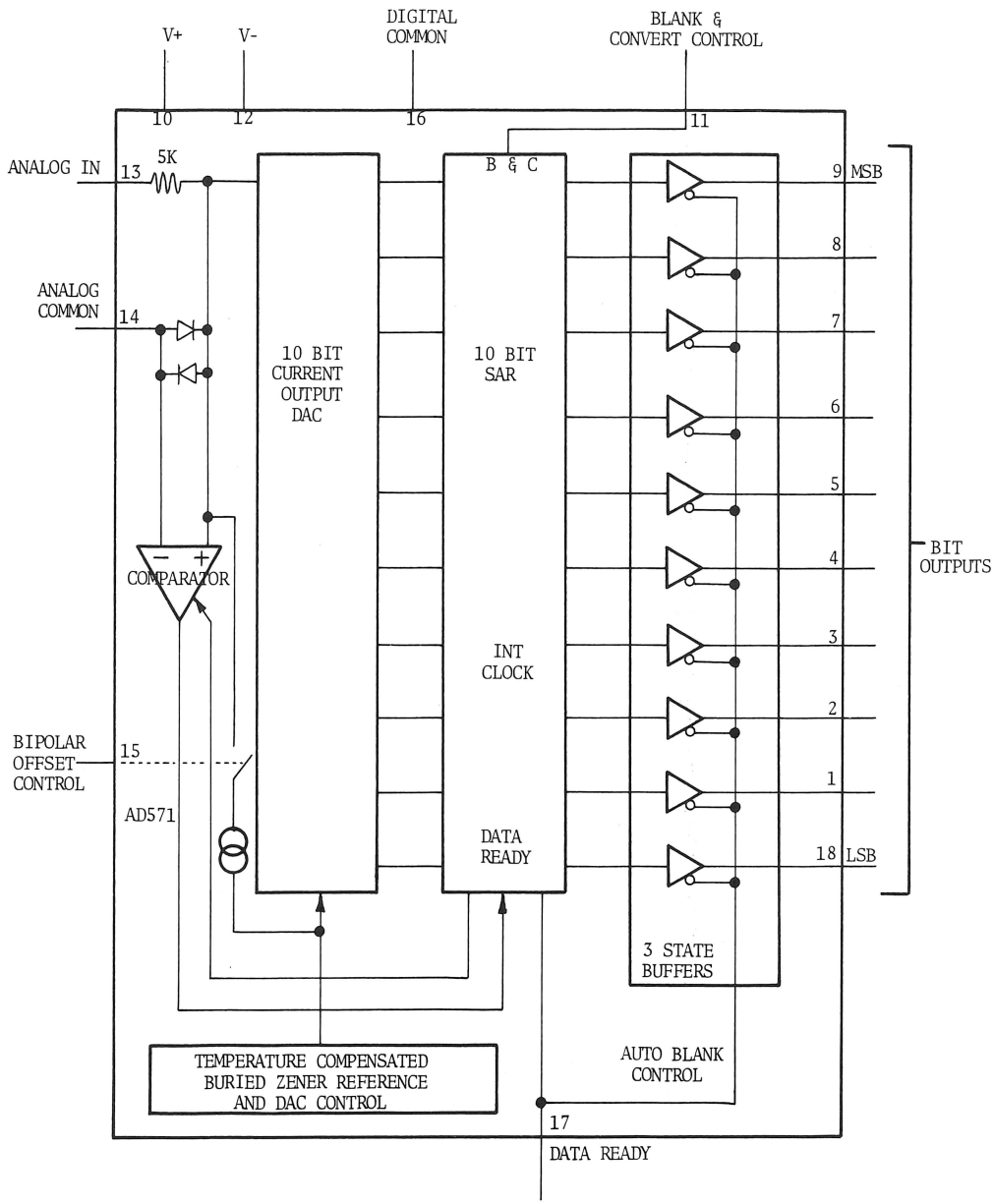


FIGURE 3.20 Sine wave (.1 Hz) digitized at 15 samples per second.

(pin 10) which can be set between + 5 and + 15 volts depending on whether you need TTL or CMOS compatability. The negative supply voltage (pin 12) is intended to be set at − 15 volts, but can be set as low as − 12 volts if necessary. The AD571 gives the designer the option of being able to configure the internal circuitry for either unipolar (0 to + 10 volts) or bipoloar (− 5 to + 5 volts) operation. If your application involves only positive signals, then the greatest resolution can be realized by operating the circuit in the unipolar mode. Grounding the BIPOLAR OFFSET CONTROL (pin 15) puts the chip in the unipolar mode, while leaving this pin "open" puts the chip in the bipolar mode. Figure 3.22 shows a way to have logic control of pin 15. When operated in the unipolar mode, 0 volts gives an output code of 0000000000 and + 10 volts gives an output code of 1111111111. When operated in the bipolar

FIGURE 3.21 Block diagram of the Analog Devices AD571 A/D converter.



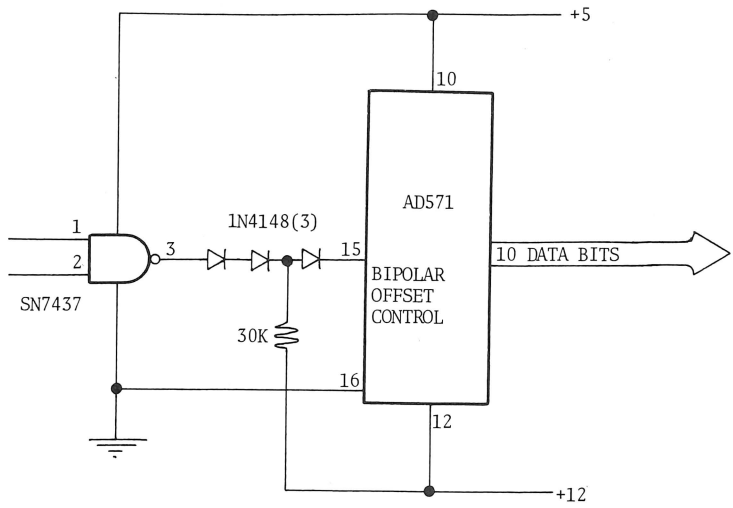


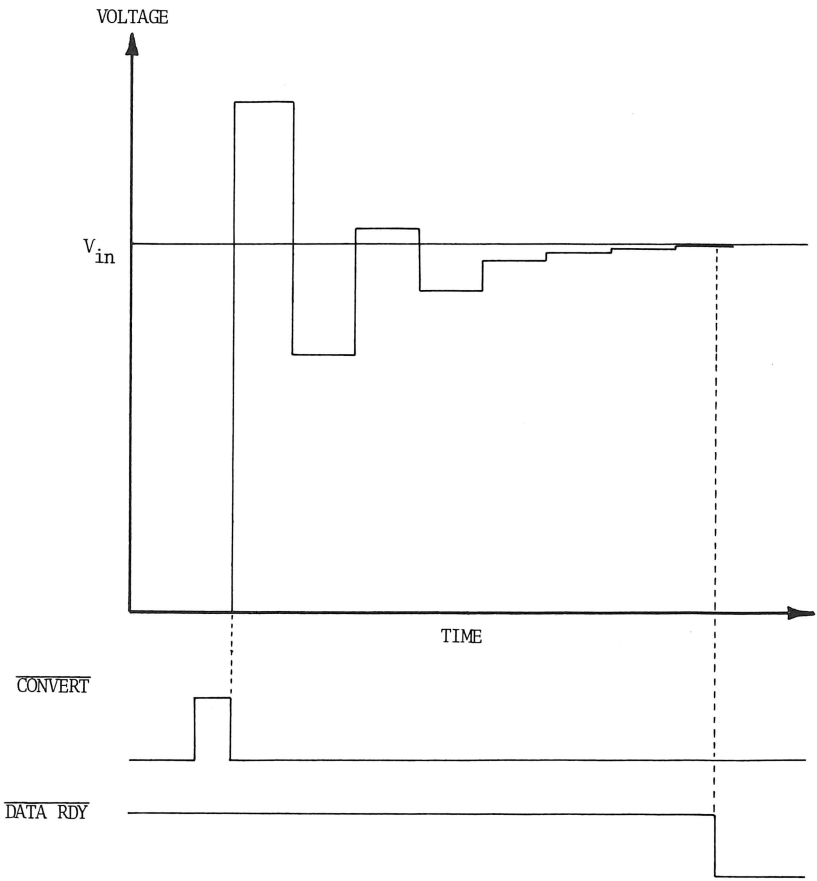
FIGURE 3.22 Bipolar Offset Control controlled by logic gate.

mode, 0 volts gives an output code of 1000000000, − 5 volts gives an output code of 0000000000, and +4.99 volts gives an output code of 1111111111. For our application, bipolar operation was desired; consequently, pin 15 was left "open."

The AD571 uses a conversion scheme known as successive-approximation to achieve the high resolution and speed necessary for some computer applications. Successive-approximation involves comparing the unknown input voltage to a preset series of voltages that are binary fractions of the maximum voltage that may be measured. Initialization of the conversion process is accomplished by providing a pulse to the control line CONVERT*. Upon receipt of the convert pulse, the internal D/A converter is sequenced from its most significant bit to its least significant bit. The internal comparator determines whether the addition of each successively-weighted bit creates a voltage which is greater or less than the input voltage. If the voltage is greater, the bit is turned OFF; if the voltage is less, the bit is left ON. After the sequence is completed, the conversion is complete and the internal successive approximation register contains the 10-bit binary code which represents the input signal. Thus, for a circuit that measures an input varying between 0 and 10.0 volts, the comparisons would be made between voltage levels that varied in 9.766E-3 volt increments (10 volts divided by 1024 discrete levels). When an unknown input voltage is to be converted, the MSB of the D/A

converter's output (½ full scale) is turned ON and the input voltage is compared to 5 volts. If the input voltage is less than 5 volts, the MSB is turned OFF, the next bit (¼ full scale) is turned ON, and the input voltage is compared to 2.5 volts. If the unknown voltage is greater than 2.5 volts, the second bit is left ON, the next bit (⅛ full scale) is turned ON, and the input voltage is compared to 3.75 volts. If the unknown voltage is less than 3.75 volts, the third bit is turned OFF, the next bit (1/16 full scale) is turned ON, and the input is compared to 3.125 volts. This process continues in order of descending bit weight until all the bits have been tried. The conversion process is thus completed and the 10-bit binary number representing the unknown input voltage is ready to be read by the computer. Figure 3.23 shows the timing relationship between the start of a conversion and the test sequence that we have described above.

FIGURE 3.23 Typical test sequence for a successive approximation A/D converter.



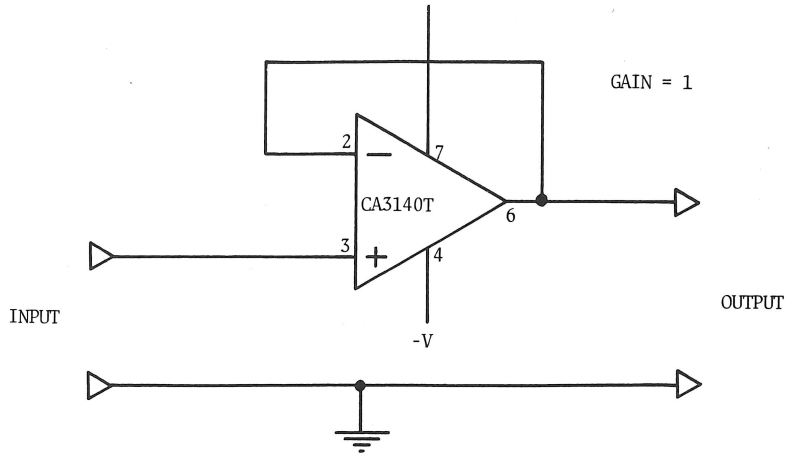


FIGURE 3.24 Noninverting, unity gain, buffer amplifier.

During the time that the conversion is being performed, the status line, DATA READY* (pin 17), goes high indicating that the converter is busy. Upon completion of the conversion, the status line goes low, bringing the three state buffers out of their "open" state and activating the bit output lines.

The typical input resistance of the AD571 is equal to 5000 ohms. Since this is low enough to excessively load some circuits, I would recommend that you use a buffer circuit to provide the necessary impedance matching. If your input voltage approaches the maximum capability of the A/D converter, then the simple unity gain, voltage-follower shown in Figure 3.24 should be adequate. If your input voltage is much less than the maximum the converter is capable of measuring, then the inverting amplifier shown in Figure 3.25 should be used. Notice that the gain of this amplifier configuration is variable, depending upon the ratio of the resistor combinations that are used. Appendix B has been provided to explain the operation of amplifier circuits, and to provide you with enough information so that you can design a specific circuit to satisfy your design requirements, if you should need to do so.

DETERMINING THE RESOLUTION While we have discussed the definition of resolution in an earlier section, I would like to make some additional comments which will help you

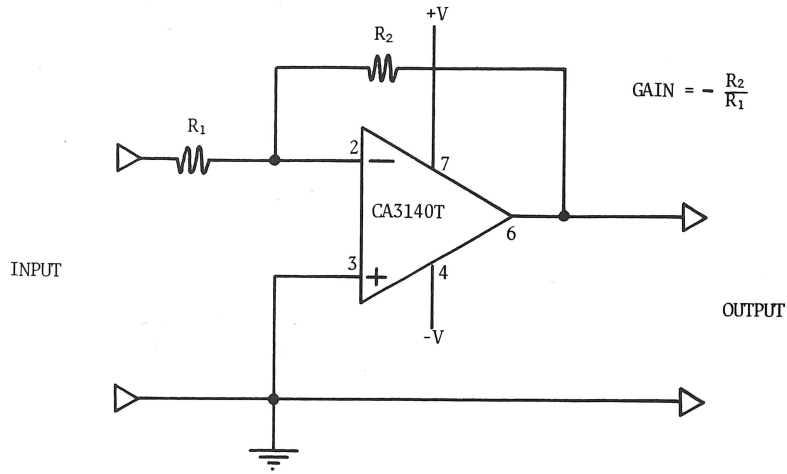


FIGURE 3.25 Inverting, adjustable gain, buffer amplifier.

determine the resolution that your particular application will require. In the process of A/D conversion, we are representing a continuous analog voltage in terms of a certain number of binary bits. We have already stated that the number of binary digits which are available to represent the analog signal is going to determine the resolution of the system, where resolution gives a measure of the converter's ability to distinguish between two voltages separated by some small voltage increment dR. For example, in Figure 3.26 we have the block diagram of a typical 8-bit A/D converter. Functioning correctly, this device will convert an analog input voltage, V_{in}, into a discrete voltage represented by the 8-bit binary number at the output. If a 0 volt signal is represented by a bit configuration equal to 00000000, and a + 10 volt signal is represented by a bit configuration equal to 11111111, then any magnitude of voltage between these extremes will be equal to a multiple of .039 volts (10 volts divided by 256 discrete levels). The converter will by necessity introduce an uncertainty—consequently, an inaccuracy—into the measurement, since the actual input voltage has to be represented by a discrete quantity at the output, and there are only so many bits which are available. It should be easy to see that we should be able to increase the accuracy of the A/D converter by increasing the resolution, that is, by increasing the number of binary output bits which are available to represent the input voltage. For example, if

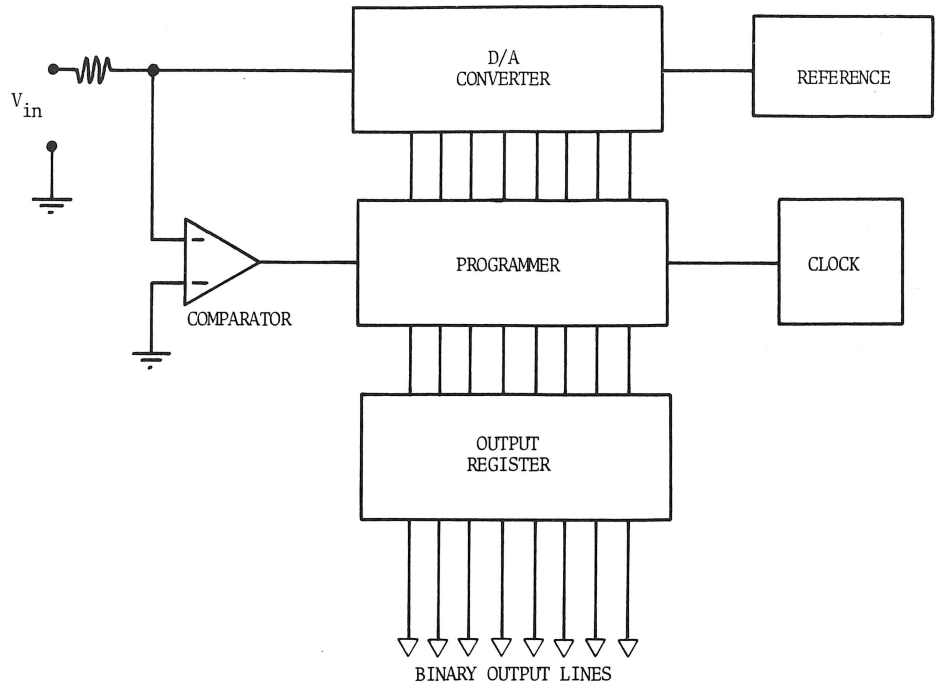


FIGURE 3.26 Block diagram of an 8-bit, successive approximation type A/D converter.

we were using a 10-bit A/D converter, we would expect the device to represent the input voltage as one of 1024 possible values. This would mean that a 0 volt signal would be represented by 0000000000, a +10 volt signal would be represented by 1111111111, and values in between these two extremes would be assigned values in steps of .00977 volts (10 volts divided by 1024 discrete levels). This is obviously an improvement over the 8-bit device.

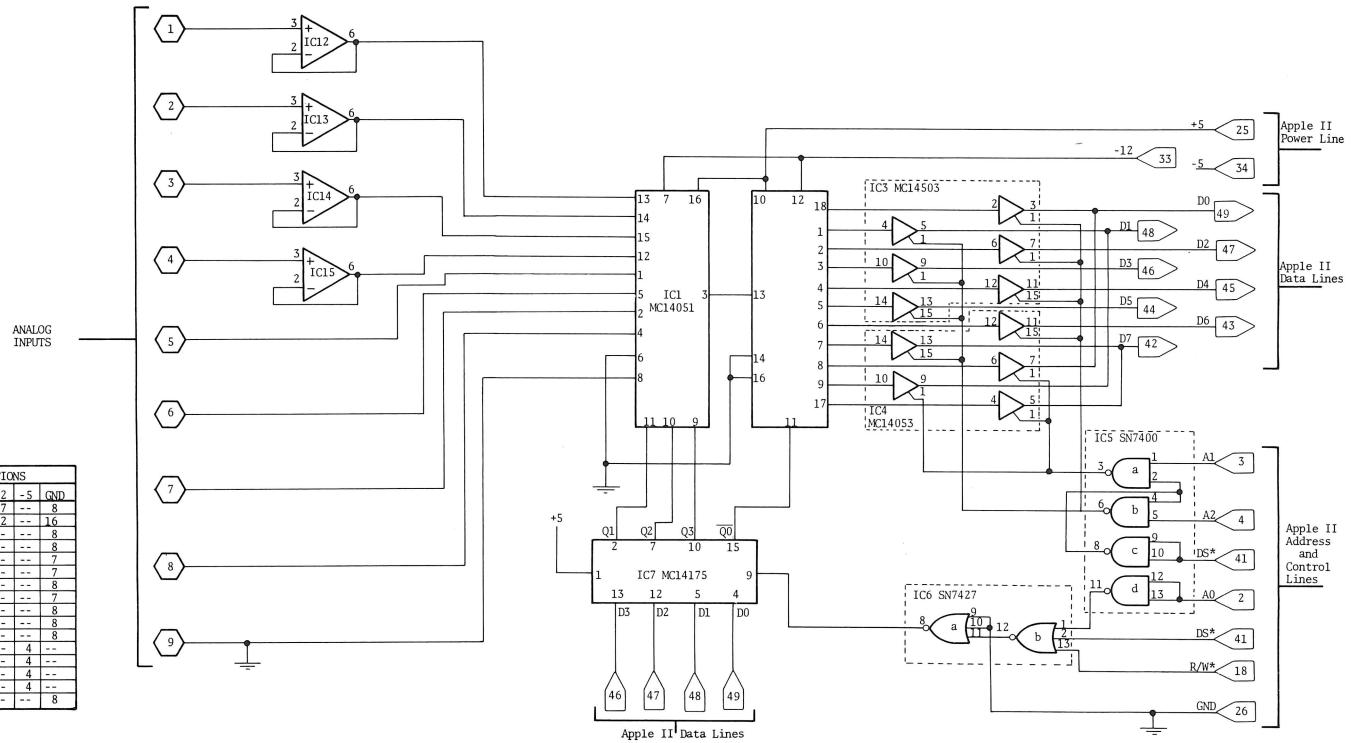
Since increased resolution usually means increased circuit cost, increased conversion time, and increased memory requirements, we need to wisely choose the number of output bits that will satisfy our particular design requirements without providing excessive capability. How then do we determine the resolution (dR) which we will need to meet the requirements of our application? Suppose we needed to determine the magnitude of the input voltage and be reasonably certain that the apparent magnitude was within 1 percent of the actual magnitude. To achieve this, we would have to have a resolution of at least 1 part in 100. To attain

this resolution, we will need at least 7 binary bits at the output. If both positive and negative quantities are to be represented, the converter will need one extra bit to represent the sign, making a total of 8 bits. While 1 percent sounds pretty good, remember that this is in reference to the maximum voltage that the converter can handle; this means that for a maximum input voltage of 10 volts, you will be able to distinguish signals that are .1 volt apart. If the input voltage is varying between 0 and + 1 volt, you still will have a resolution equal to .1 volt, but your accuracy will have decreased to 10 percent (1/ .1). Keep in mind that for this discussion, I am assuming that the primary source of inaccuracy in our system is due to a lack of resolution. To determine a measure of your system's ability to differentiate between the magnitude of two voltages, follow these steps:

1. Determine the magnitude of the signal that you will be measuring.
2. Determine the maximum resolution of your system by dividing the magnitude of the output signal which corresponds to all 1's, by the number of discrete voltage steps which the system is capable of providing. Do not count sign bits.
3. Divide the quantity from Step 2 by the quantity from Step 1 and multiply by 100 to get the accuracy expressed in percent.

You should realize that in Step 1 you were concerned with the magnitude of the signal that you would be measuring, not the magnitude of the signal that you were capable of measuring. The truncating and rounding procedure that the A/D converter performs to get the input signal to fall into predetermined voltage slots has the effect of causing the accuracy to vary as a function of the magnitude of the input signal (even though resolution remains constant). For this reason, you should always be aware of the magnitude of the signal which you will be measuring; often, the system you choose will have to be a compromise between accuracy and dynamic range.

Figure 3.27 shows a schematic diagram of a high-speed A/D converter for the Apple II, and Figure 3.28 shows a schematic diagram of a crystal controlled time base oscillator which we will be using to determine the sampling rate. IC1 is an analog multiplexer which is used to select one of eight possible input signals. Control of input signal selection is accomplished by latching a given bit pattern at the output pins of the quad type D flip-flop



IC POWER CONNECTIONS

IC #	TYPE	+5	-12	-5	GND
1	MC14051	16	7	--	8
2	AD571	10	12	--	16
3	MC14503	16	--	--	8
4	MC14503	16	--	--	8
5	SN7400	14	--	--	7
6	SN7427	14	--	--	7
7	MC14175	16	--	--	8
8	MC14001	14	--	--	7
9	MC14518	16	--	--	8
10	MC14518	16	--	--	8
11	MC14518	16	--	--	8
12	CA3140T	7	--	4	--
13	CA3140T	7	--	4	--
14	CA3140T	7	--	4	--
15	CA3140T	7	--	4	--
16	MC14528	16	--	--	8

FIGURE 3.27 High-speed A/D converter for the Apple II.

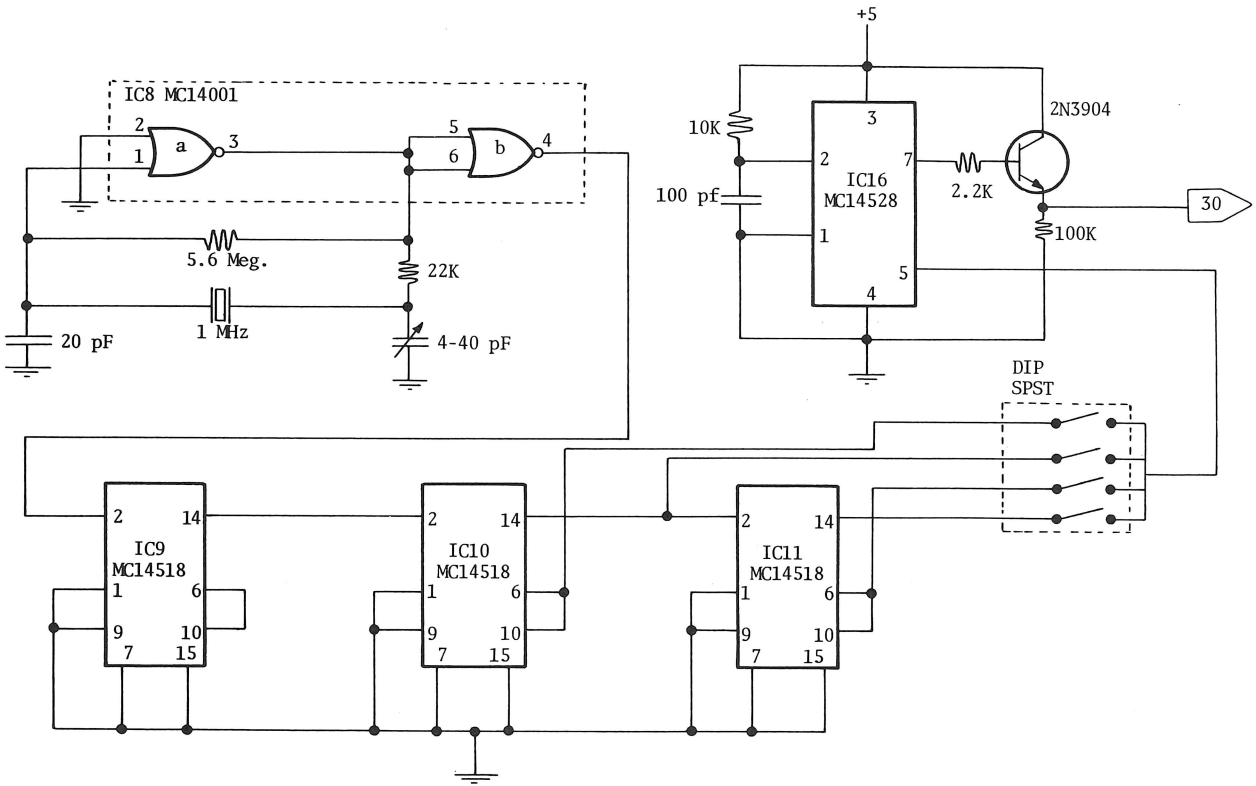


FIGURE 3.28 Crystal-controlled time base oscillator.

(IC7). You should notice that one of the lines from the flip-flop is connected to the A/D converter. This is the control line (CONVERT*), discussed earlier in the overview of the AD571 A/D converter (IC2), which is used to signal that a conversion is to begin. Data lines D0, D1, and D2 then control the selection of the analog input signal, and D3 controls the initiation of the conversion process. If you executed the following BASIC commands, you would convert the analog signal present at input 2 into a digital quantity.

```
100 POKE -16143,09
110 POKE -16143,01
```

IC12, IC13, IC14, and IC15 are operational amplifiers which are configured as unity gain, noninverting buffers. They are used to isolate an input signal from the input of the AD571 to avoid problems associated with the relatively low input resistance of this device. Four unbuffered inputs are also provided for input signals which do not need to be isolated (having a low value of series output resistance), or which require an additional stage of amplification.

All the data and status lines to the Apple II have been isolated through use of the MC14503 three-state buffers (IC3 and IC4). Since the Apple II is an eight-bit machine, the 10 bits from the AD571 are transferred to memory in a two-step operation. The DATA RDY* line and the two most significant bits are read into the machine through the use of an LDA $C0F2 machine language command. When the AD571 signals the Apple II that a conversion has been completed (by dropping DATA RDY* to 0 volts), the following sequence of operations should be performed:

1. The most significant two bits of data (appearing on D0 and D1 of the data bus) should be stored in memory.
2. The least significant eight bits should be transferred into the computer through the use of an LDA $C0F4 machine language command and stored in memory.
3. The Apple II should then either process the data or return to gather more data.

IC8 and the 1 MHz crystal provide a stable pulse train which is used to determine the sampling frequency. IC9, IC10, and IC11 divide the 1 MHz pulse train by multiples of ten so that sampling rates of 1, 10, 100, and 1000 samples per second can be obtained. IC16 is a monostable multivibrator which is used to provide an inverted output pulse, width being independent of the output frequency, to the Apple II I/O interrupt input. The 2N3904 transistor is configured as an emitter follower to provide the current drive requirements necessary to drive the interrupt line.

Once you have constructed the interface, connect it to the Apple II and perform the following tests to make sure that it is working correctly:

1. If you execute the following BASIC statements, pin 7 and pin 2 on IC7 should go to +5 volts. Pin 10 and pin 15 should remain at 0 volts.

```
100 POKE -16143,09
```

2. If you execute the following BASIC statements, pin 2 on IC7 should go to 0 volts. Pin 7 should remain at +5 volts. Pin 10 and pin 15 should remain at 0 volts.

```
100 POKE -16143,01
```

3. If you now apply an analog signal to input IN1, you should see that signal at the output (pin 3) of the multiplexer (IC1).

If you have an oscilloscope, you can perform the following tests and adjustments:

1. If you execute the following BASIC statements, you should see the DATA RDY* line periodically go from 0 to +5 volts.

```
100 POKE -16143,09
110 POKE -16143,01
140 FOR I=1 TO 100
142 NEXT I
150 GOTO 100
```

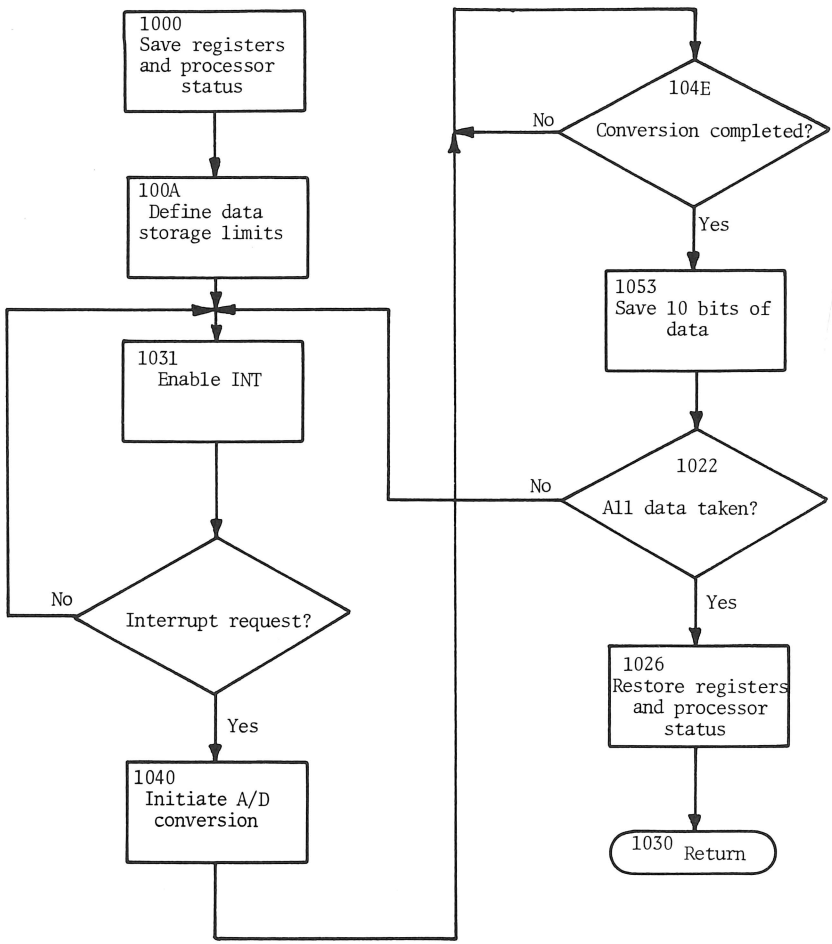
2. Adjust the 4-40 pf trimmer capacitor in the crystal oscillator until the output of IC8 is equal to 1 MHz. The IRQ* line should reflect the sampling frequency that you have selected.
3. Measure the pulse width of the output of IC16. It should be approximately equal to .1 milliseconds.

The software portion of the high speed A/D converter interface was handled in two parts:

1. A routine written in Applesoft BASIC takes the binary representation of the analog data and converts it into a decimal number which then can be displayed, or stored for future reference.
2. A machine language routine which was written to control the AD571 and to provide high speed transfer of the binary data into the Apple II.

Figure 3.29 shows a flow chart for the machine language routine, and Listing 3.6 gives the actual program with comments. Upon entering the subroutine, all necessary registers are saved to allow

FIGURE 3.29 Flow chart for the machine language routine for controlling the high-speed A/D converter.



LISTING 3.6 Machine language program for the high-speed A/D converter.

```
1000   8D FD 10      STA  $10FD     SAVE REGISTERS
1003   8C FF 10      STX  $10FE
1006   8C FF 10      STY  $10FF
1009   08            PHP            SAVE PROC STATUS
100A   A9 00         LDA  #$00      LOAD DATA START ADR
100C   85 0A         STA  $0A
100E   A9 11         LDA  #$11
1010   85 0B         STA  $0B
1012   A9 00         LDA  #$00      LOAD DATA STOP ADR
1014   8D FB 10      STA  $10FB
1017   A9 40         LDA  #$40
1019   8D FC 10      STA  $10FC
101C   A2 00         LDX  #$00      CLEAR X REGISTER
101E   78            SEI            DISABLE INTERRUPT
101F   AD FC 10      LDA  $10FC     END OF DATA STORAGE?
1022   C5 0B         CMP  $0B
1024   D0 0B         BNE  $1031
1026   AD FD 10      LDA  $10FD     RESTORE REGISTERS
1029   AE FE 10      LDX  $10FE
102C   AC FF 10      LDY  $10FF
102F   28            PLP            RESTORE PROC STATUS
1030   60            RTS            RETURN TO BASIC
1031   58            CLI            ENABLE INTERRUPT
1032   EA            NOP
1033   4C 1E 10      JMP  $101E
1036   00            BRK
1037   00            BRK
1038   00            BRK
1039   00            BRK
103A   00            BRK
103B   00            BRK
103C   00            BRK
103D   00            BRK
103E   00            BRK
103F   00            BRK
1040   A9 09         LDA  #$09      BEGIN CONVERSION
1042   8D F1 C0      STA  $C0F1
1045   A9 01         LDA  #$01
1047   8D F1 C0      STA  $C0F1
104A   AD F2 C0      LDA  $C0F2     GET DATA
104D   2A            ROL            ROTATE LEFT
104E   B0 FA         BCS  $104A
1050   6A            ROR            ROTATE RIGHT
1051   29 03         AND  #$03      SAVE 3 BITS
1053   81 0A         STA  ($0A,X)   SAVE DATA
1055   A4 0A         LDY  $0A
1057   C8            INY            INCREMENT STORAGE ADR
1058   84 0A         STY  $0A
105A   D0 05         BNE  $1061
105C   A4 0B         LDY  $0B
105E   C8            INY
105F   84 0B         STY  $0B
1061   AD F4 C0      LDA  $C0F4     GET DATA
1064   81 0A         STA  ($0A,X)   SAVE DATA
1066   A4 0A         LDY  $0A
1068   C8            INY
1069   84 0A         STY  $0A
106B   D0 05         BNE  $1072
106D   A4 0B         LDY  $0B
106F   C8            INY
1070   84 0B         STY  $0B
1072   A5 45         LDA  $45
1074   40            RTI            RETURN FROM INTERRUPT
```

a successful return to the BASIC calling routine. The program then defines the data storage space and initializes the system I/O bus. The interrupt request line is then activated and the program loops until an interrupt request is made. The request for an interrupt comes from the output of the crystal time base oscillator, the frequency being dependent upon the position of switch S1. After

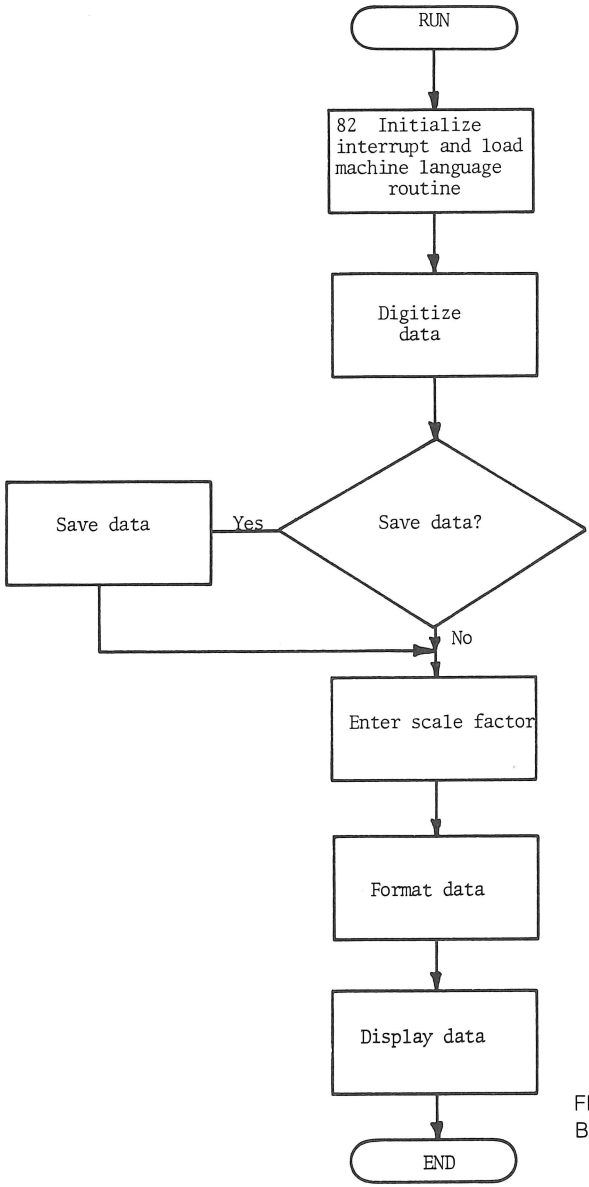


FIGURE 3.30 Flow chart for the BASIC routine.

receiving an interrupt request, the program initiates an A/D conversion, and waits until the AD571 signals that the conversion is completed. The 10 data bits are then stored in memory and the program tests to see if the data storage is filled. If all the data storage has been filled, the program restores all the necessary registers and returns to the BASIC calling routine. If all the data storage has not been filled, the program returns to activate the interrupt system and to take more data.

Figure 3.30 shows a flow chart for the BASIC program, and Listing 3.7 gives the actual program with comments. The BASIC routine first loads the machine language routine by using the READ and POKE statements. Then the machine language routine is called to obtain a block of digitized analog data. When the

LISTING 3.7 BASIC program for the high-speed A/D converter.

```
80 HIMEM:4096
82 POKE 1022,64:POKE 1023,16:POKE 1016,72:POKE 1017,8
83 POKE 1018,120:POKE 1019,40:POKE 1020,104:POKE 1021,96
84 CALL 1016
90 FOR I=4096 TO 4212:READ D:POKE I,D:NEXT I
100 HOME:VTAB 12:PRINT "DATA BEING DIGITIZED"
102 CALL 4096
105 HOME:VTAB 12:PRINT "WHAT IS THE TIME SCALE?"
106 GET K:HOME:VTAB 12
107 PRINT "DO YOU WANT TO SAVE THE DATA?":INPUT K$
108 IF K$="N" THEN GOTO 120
109 IF K$="Y" THEN GOTO 115
110 GOTO 106
115 D$=""
116 PRINT D$;"BSAVE DATA($1100),A$1100,L$2F00
120 HOME:HGR2:HCOLOR=3:X=4352
130 FOR J=0 TO 240/K
135 X=X+2:IF X>16382 THEN GOTO 230
140 V1=PEEK(X):V2=PEEK(X+1)
142 IF V1>1 THEN GOTO 200
150 Z=-(511-(V1*256+V2))/5
160 HPLOT K*J,90-Z
170 NEXT J
190 HGR2:HCOLOR=3:GOTO 130
200 Z=((V1-2)*256+V2)/5
210 HPLOT K*J,90-Z:GOTO 170
230 TEXT:END
1000 DATA 141,253,16,142,254,16,140,255,16,8,169,0,133,
          10,169
1002 DATA 17,133,11,169,0,141,251,16,169,64,141,252,16,
          162,0
1004 DATA 120,173,252,16,197,11,208,11,173,253,16,174,
          254,16
1006 DATA 172,255,16,40,96,88,234,76,30,16,0,0,0,0,0,0,
          0,0,0,0
1008 DATA 169,9,141,241,192,169,1,141,241,192,173,242,
          192,42,176
1010 DATA 250,106,41,3,129,10,164,10,200,132,10,208,5,
          164,11,200
1012 DATA 132,11,173,244,192,129,10,164,10,200,132,10,208
1014 DATA 5,164,11,200,132,11,165,69,64
```

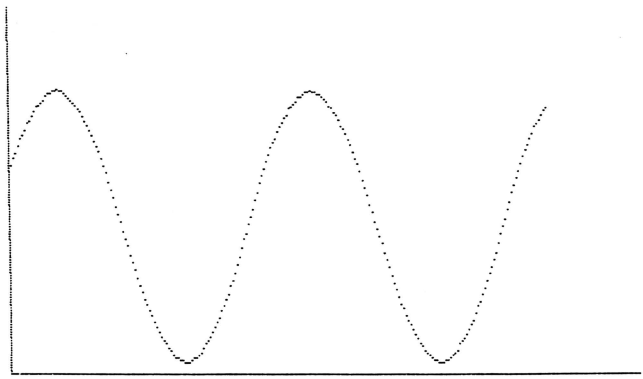


FIGURE 3.31a 10 Hz sine wave digitized at 1000 samples per second.

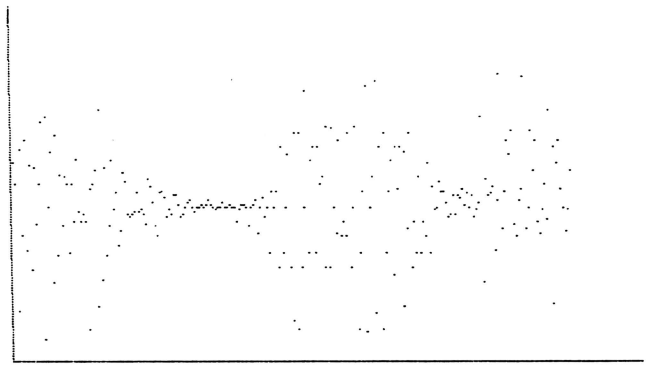


FIGURE 3.31b Music digitized at 1000 samples per second.

program returns from the machine language routine, the BASIC program then reconstructs the data into a voltage and plots the voltage on the video monitor. Figure 3.31a shows the results of digitizing a 10 Hz sine wave at a sampling rate of 1000 samples per second. Figure 3.31b shows the results of digitizing music at a sampling rate of 1000 samples per second.

The program is configured so that you can save the digitized data. This will allow you to recover the data for further analysis. (In Chapter 8 we will use this feature to analyze a complex waveform and determine frequency components.) The program also allows you to expand the displayed data. Figure 3.32a shows a 100 Hz sine wave digitized at a sampling rate of 1000 samples per second and not expanded. Figure 3.32b shows the same block of data displayed with an expansion factor of 5.

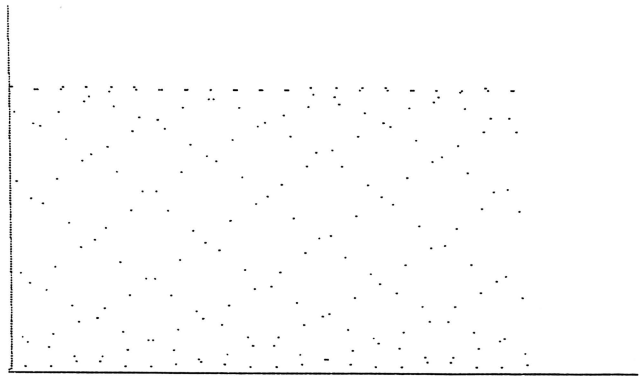


FIGURE 3.32a 100 Hz sine wave digitized at 1000 samples per second ($^{x}1$).

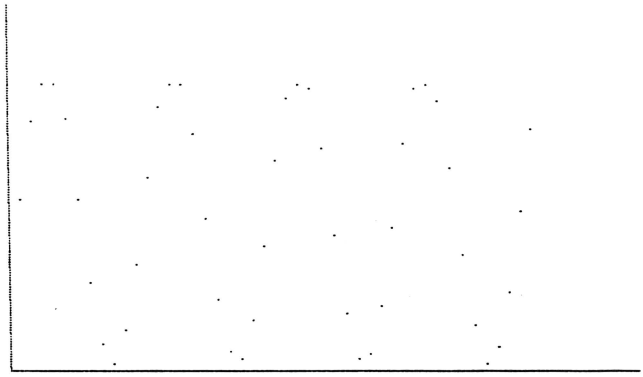


FIGURE 3.32b 100 Hz digitized at 1000 samples per second ($^{x}5$).

4

DIGITAL-TO-ANALOG CONVERSION

Digital-to-analog (D/A) converters are devices that take a digital input—usually from the data bus of a computer—and convert it into an analog signal. While the analog signal is often thought of as being a continuous quantity, the output of the D/A converter will actually consist of a series of discrete and easily measurable voltages. Resolution, the voltage difference between steps, will depend upon the number of bits that the D/A converter can handle.

The Analog Devices AD558 DACPORT is an 8-bit digital-to-analog converter that includes a precision voltage reference, a microprocessor interface, a data latch, and an output amplifier—all on a single monolithic chip. Thin film silicon-chromium resistors are used in a current-driven ladder to provide an analog voltage that is stable over a large temperature range. Figure 4.1

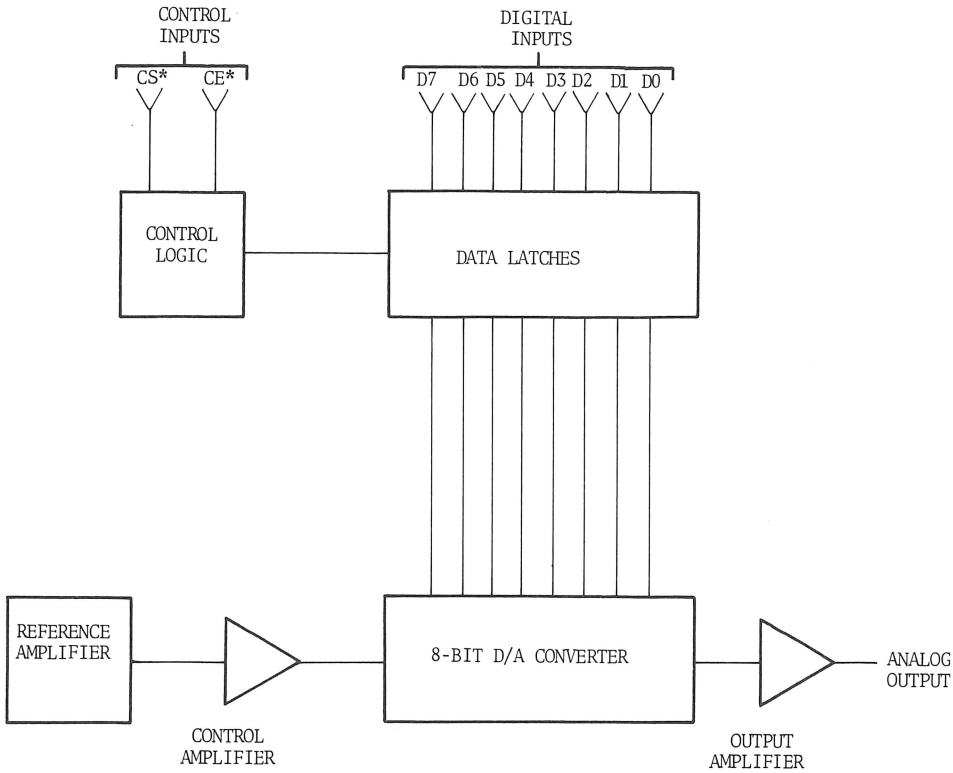


FIGURE 4.1 Functional block diagram of the AD558.

shows a functional block diagram of the AD558. The data latch is connected to the computer data bus, data being accepted when both control inputs, CE* and CS*, are low. When either control input returns high, the 8-bit data word is latched and the analog output is unaffected by further activity on the data lines. For a maximum output voltage of 2.56 volts, the resolution of the converter will be equal to 0.1 volts; that is, a change in the least significant digit will result in .01 volt change in the output voltage.

Figure 4.2 shows the schematic diagram for a D/A converter interface for the Apple II. Data is strobed into the converter by writing data to the appropriate I/O slot. The analog output will then remain stable until new data is written.

After you have finished building the interface, perform the following tests to make sure that it is working correctly:

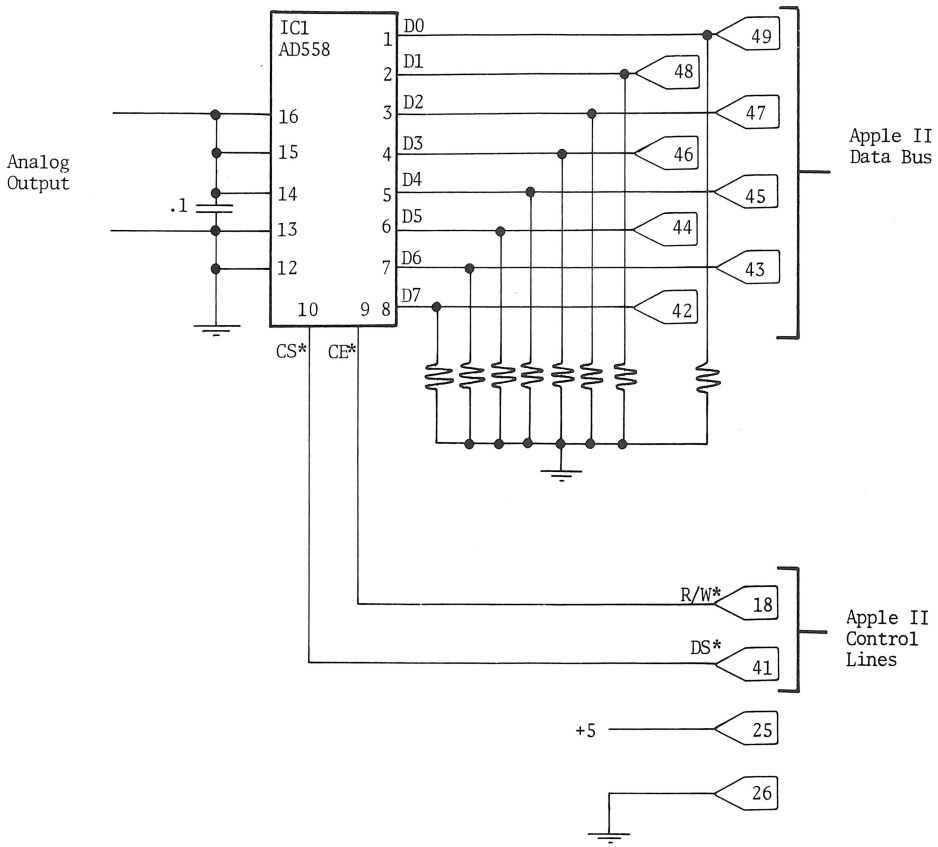


FIGURE 4.2 Interface schematic for the AD558 D/A converter.

If you execute the following BASIC statements, you should see the analog output ramp from 0 volts to 2.55 volts.

```
110 FOR I=0 TO 255
120 POKE -16143,I
130 NEXT I
199 END
```

Digital-to-analog converters are commonly used in digitally-controlled power supplies for automated test equipment, digital generation of analog waveforms, and digital control of automatic process control systems. I will present examples of two automatic test equipment systems that might be constructed to perform quality control testing in a manufacturing facility.

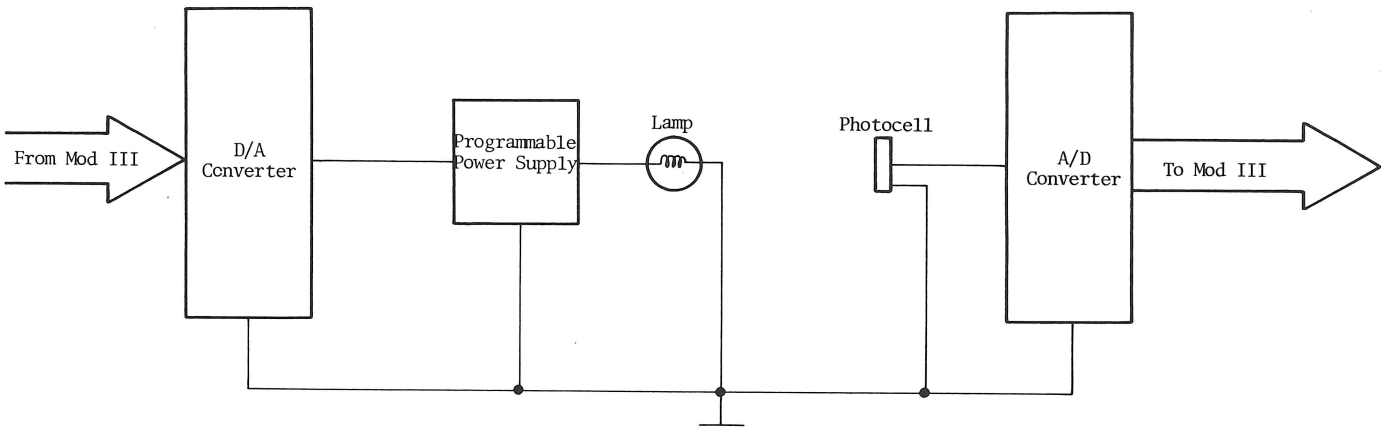
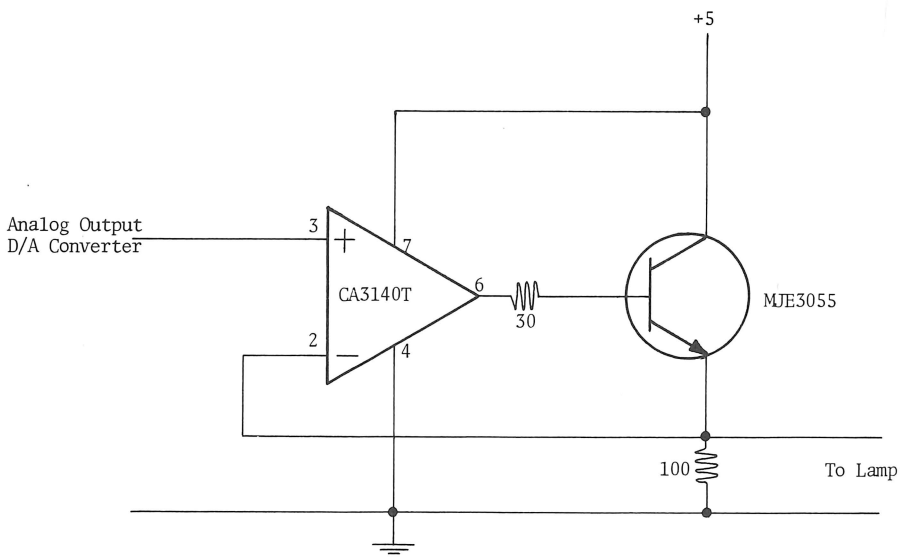


FIGURE 4.3 Block diagram of proposed testing arrangement.

The first example involves cycling an incandescent lamp through a number of voltages to determine if the lamp intensity is acceptably high. The lamp might be used in a simple colorimeter for a chemistry laboratory, and its intensity may need to be above a certain level to ensure reliable operation. Since checking each lamp could be very time consuming, it would be desirable to have the computer automatically increase the lamp voltage and record the lamp intensity at each voltage. At the end of the test, the computer could then make a decision regarding the acceptability of the lamp. The output of the AD558 is already buffered, but by itself cannot provide enough current to drive an incandescent lamp. What we will do is build a voltage programmable power supply, one whose output voltage is some multiple of the input voltage supplied by the A/D converter.

Figure 4.3 shows a block diagram of the proposed testing arrangement. The data bus from the Apple II will supply a binary number that will be converted by the D/A converter into an analog voltage. This voltage will then be used to control the lamp voltage. Lamp intensity will be monitored by a photocell connected to the high speed A/D converter which we discussed in Chapter 3. Figure 4.4 shows a schematic diagram of the programmable power supply. Figure 4.5 shows a flow chart for an Applesoft BASIC program to cycle the lamp voltage from 0 to 2.0 volts. Listing 4.1 shows the actual program with comments.

FIGURE 4.4 Schematic diagram of lamp power supply.



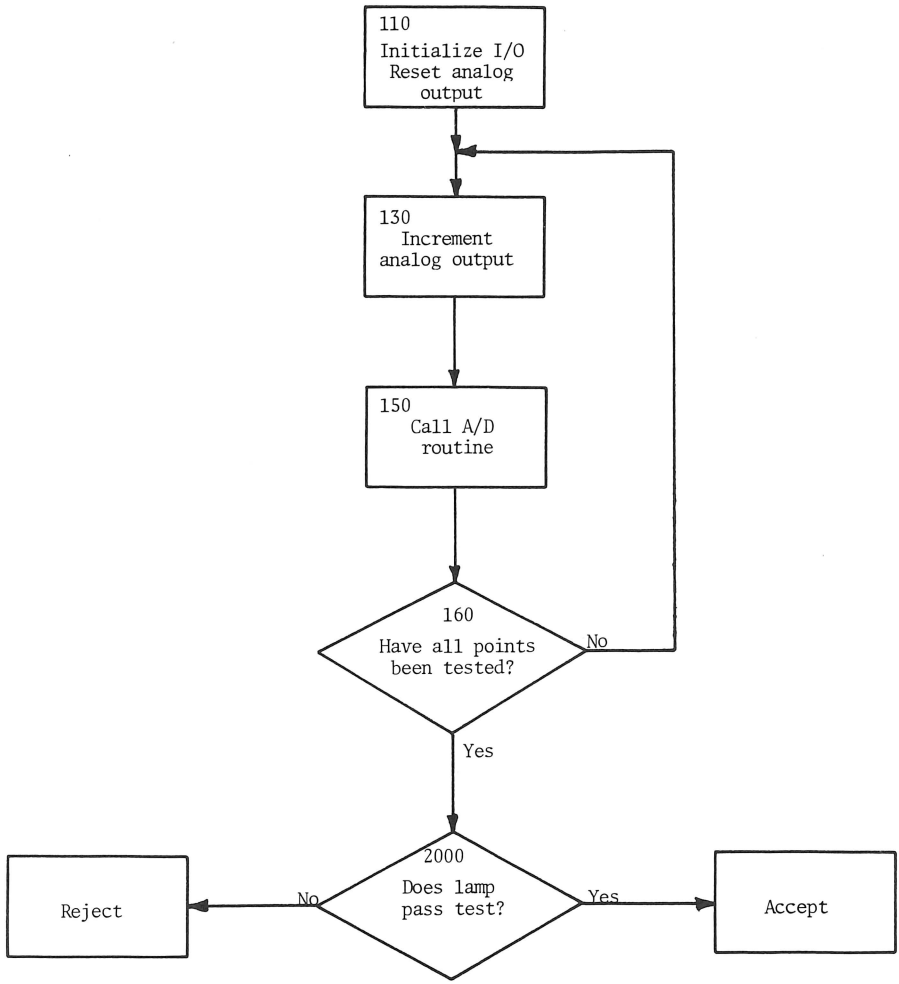


FIGURE 4.5 Flow chart of BASIC program for automatic testing of incandescent lamps.

LISTING 4.1 BASIC routine for lamp test example.

```
100 REM LAMP TEST ROUTINE
102 REM R. HALLGREN, 10-27-81
104 REM APPLE II
120 FOR I=1 TO 10
130 POKE -16143,20*I
140 FOR J=1 TO 500:NEXT J
150 GOSUB 1000
160 NEXT I
170 GOSUB 2000
199 END
1000 REM ANALOG-TO-DIGITAL SUBROUTINE
1999 RETURN
2000 REM LAMP PASS/NOT PASS SUBROUTINE
2999 END
```

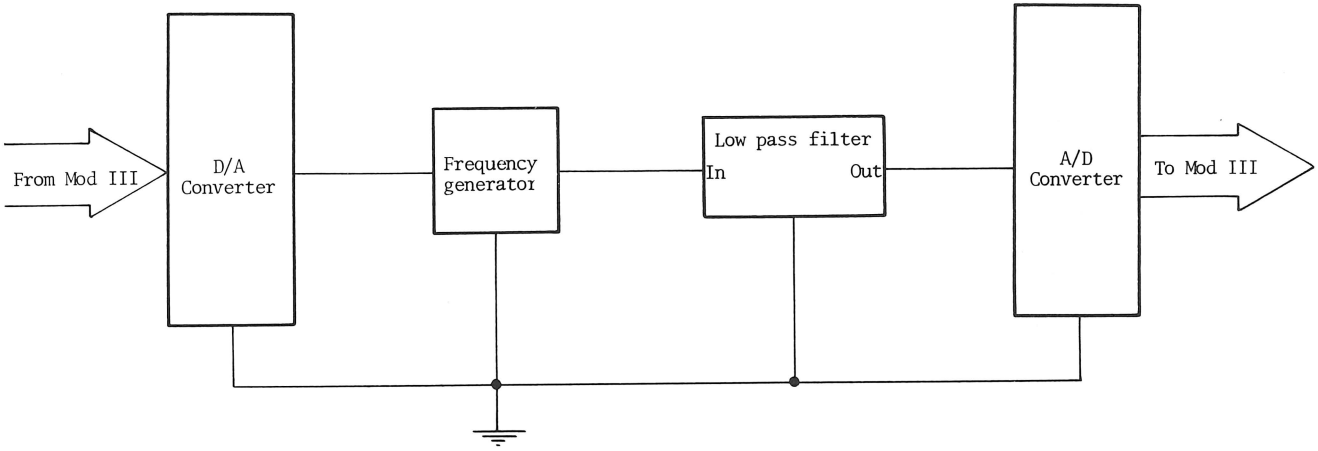


FIGURE 4.6 Block diagram for low-pass filter testing arrangement.

The second example involves testing the frequency response of a low pass filter. We will use the D/A converter to directly control the output frequency of a B&K 3010 Function Generator (Dynascan Corporation, 6460 W. Cortland Street, Chicago, Illinois 60635). This instrument has an input jack which allows an external voltage to directly control its output frequency. Figure 4.6 shows a block diagram of the proposed testing arrangement. Again, the data bus from the Apple II will supply a binary number which will be converted by the D/A converter into an analog voltage. This voltage will then be used to control the frequency of the function generator. The output of the low pass filter could be monitored by connecting it to the high speed A/D converter, and the computer could determine if the 3db cutoff frequency is within acceptable limits.

For both of the examples that we have looked at, the goal was to reduce the amount of personnel time required to perform a routine test operation. This was accomplished through the use of a computer-controlled test protocol.

5

UTILIZATION OF THE APPLE II IN SERIAL APPLICATIONS

HIGH RESOLUTION DIGITAL PLOTTING

Utilization of personal computers, such as the Apple II, in business and research applications has met with considerable success. Not only do they function as computational tools but, when used in conjunction with peripheral devices, they can perform complex functions at reduced expense. The research laboratory often deals with complex, time-dependent waveforms. This type of data can be easily digitized (see Chapter 3) and analyzed (see Chapter 8), but a major problem arises when a permanent copy of the data is required. Printing a column of numbers does little to convey to the researcher the nature of the data, especially several months after the data are taken. Plotting with a terminal such as the Decwriter II is possible, but lacks the necessary resolution for

many applications. The HIPLOT Digital Plotter, manufactured by Houston Instruments, gives the researcher a cost effective means of obtaining quality digital plots. The plotter accepts an 8½ x 11 inch sheet of paper and allows plotting within a 7 x 10 inch boundary. Reversible stepper motors are used to give bidirectional steps of either 200 or 100 steps per inch, amounting to a resolution of .005 or .01 inches per step respectively. The plotter comes with a standard RS-232C serial interface, so interfacing it to the computer is a relatively straightforward task.

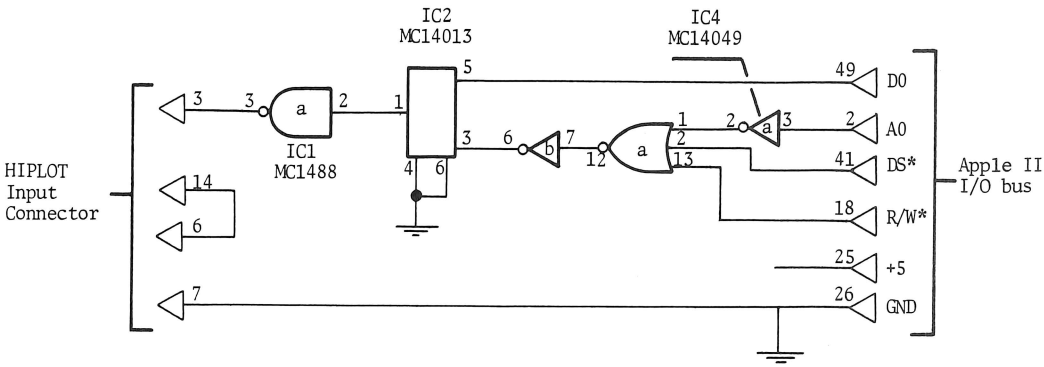


FIGURE 5.1 HIPLOT and Apple II interface connections.

We have already discussed the serial data format in Chapter 2, and we have examined the necessary hardware (see Figure 2.9) and software (see Listing 2.1) to implement a TTL to RS232-C conversion. If you have not already built this circuit, you should do so now. Since we will be using the power supply in the Apple II, you will not need to provide any additional voltages. Once you have constructed the interface, connect it to the plotter as shown in Figure 5.1 and insert the circuit board into I/O slot 5. Perform the following tests to make sure that it is working correctly:

1. If you execute the following BASIC statement the output of IC1 should go to +10 volts.
   POKE −16175,0
2. If you execute the following BASIC statement the output of IC1 should go to −10 volts.
   POKE −16175,1
3. Load and execute the BASIC program shown in Listing 5.1. If everything is working correctly, the plotter pen should begin mov-

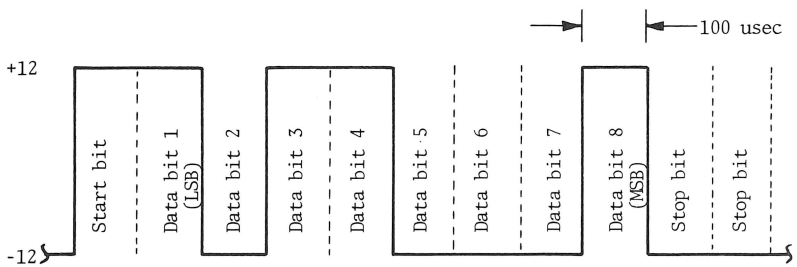
LISTING 5.1 Digital plotter demonstration program.

```
10 REM DIGITAL PLOTTER DEMO
12 REM APPLE II
14 REM R. HALLGREN, 9-15-81
20 FOR I=0 TO 160:READ D:POKE (-32800+I),K:NEXT I
50 FOR I=1 TO 100
52 CALL -32695
54 NEXT I
99 END
10000 DATA 160,9,24,72,176,7,169,0,141,209,192,144,5,169,
          1,141,209,192,169,3
10002 DATA 72,169,4,74,144,253,104,233,1,208,245,104,106,
          136,208,223,160,2,169
10004 DATA 1,141,209,192,169,3,72,169,4,74,144,253,104,
          233,1,208,245,136,208
10006 DATA 235,96,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
          0,0,0,0,0,0,0,0
10008 DATA 72,8,169,112,32,224,127,40,104,96,72,8,169,113,
          76,60,128,72,8,169,114
10010 DATA 76,60,128,72,8,169,115,76,60,128,72,8,169,116,
          76,60,128,72,8,169,117
10012 DATA 76,60,128,72,8,169,118,76,60,128,72,8,169,119,
          76,60,128,72,8,169,121
10014 DATA 76,60,128,72,8,169,122,76,60,128
```

ing toward the right hand side of the platen. If you execute the program and nothing happens, you should borrow an oscilloscope and check both the bit pattern and the bit spacing of the serial data. Figure 5.2 shows the bit pattern and spacing that should be obtained.

Being able to accomplish the transfer of information in an RS232-C format is only the first step towards using the plotter. The HIPLOT consists of two stepper motors which control the X,Y position of the plotter pen. Control of the pen position, and all other plotter functions, is accomplished by sending specific control characters to the device. Figure 5.3 shows the axis system for the plotter pen, and Table 5.1 shows the character that produces an increment of the pen along the given vector. Also included are

FIGURE 5.2 Bit pattern and spacing of RS232-C output from the demonstration program



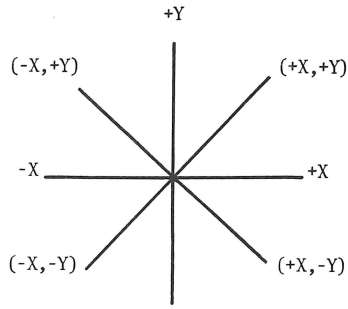


FIGURE 5.3 HIPLOT vector notations.

TABLE 5.1 HIPLOT command characters.

Command	Character	BASIC Address
+Y	p	9110
+X,+Y	q	9120
+X	r	9130
+X,-Y	s	9140
-Y	t	9150
-X,-Y	u	9160
-X	v	9170
-X,+Y	w	9180
Pen up	x	9200
Pen down	y	9210

the characters that produce control functions such as PEN UP. Since the plotter comes without any software, it is necessary to write subroutines to generate an axis system, to lable the axis, and to plot the data.

Listing 5.2 shows a program which provides some of these capabilities. Figure 5.4 shows a flow chart for the BASIC program. This program draws an X,Y axis system, lables the system with numeric characters, and plots an exponential increase in voltage as a function of time. Figure 5.5 shows a series of plots taken for increasing values of the time constant. The software was written so that the entire plot could be scaled to different dimensions. Figure 5.6 shows the maximum range of plot size. It should be obvious to the reader that the program will most likely have to be modified to meet the requirements of the specific application. The program shown in Listing 5.2 was written in a very general sense

LISTING 5.2 BASIC program for operation of the digital plotter.

```
10  REM  DIGITAL PLOTTER
12  REM  APPLE II
14  REM  R. HALLGREN     9-15-81
20  FOR I = 0 TO 160: READ K
22  POKE ( - 32800 + I),K
24  NEXT I
100  REM  MAIN PROGRAM
110  HOME : VTAB 12
112  PRINT "POSITION PEN IN LOWER LEFT HAND"
114  PRINT "CORNER. PRESS ANY KEY TO CONTINUE."
116  GET A$
118  HOME
120  PRINT "INPUT THE SCALE FACTOR(3<K<19)"
122  INPUT K
124  IF K < 4 OR K > 18 THEN  GOTO 118
128  HOME
140  GOSUB 1000
150  GOSUB 2000
200  REM  PLOT DEMONSTRATION
202  CALL  - 32646
210  FOR I = 0 TO .5 * K STEP .005
220 V = 5 * (1 -  EXP ( - 10 * I / K))
222 L =  INT (10 * K * V)
224  IF L - Z = 0 THEN  GOTO 250: REM  NO CHANGE IN POTENTIAL
226  IF L - Z < 0 THEN  GOTO 240: REM  POTENTIAL IS DECREASING
228  FOR J = 1 TO (L - Z): REM  POTENTIAL IS INCREASING
230  CALL  - 32712
232  NEXT J
234  GOTO 248
240  FOR J = 1 TO (Z - L)
242  CALL  - 32681: NEXT J: REM  MOVE PEN IN -Y DIRECTION
248 Z = L
250  CALL  - 32695: NEXT I: REM                MOVE PEN IN +X DIRECTION
299  END
1000  REM  X-AXIS
1010  CALL  - 32653
1012  FOR I = 1 TO 100 + 3 * K: CALL  - 32712: NEXT I
1013  FOR I = 1 TO K + 90: CALL  - 32695: NEXT I
1014  CALL  - 32646
1016  FOR I = 1 TO 100 * K: CALL  - 32695: NEXT I
1020  GOSUB 1900
1030  CALL  - 32653
1032  FOR I = 1 TO 3 * K: CALL  - 32667: NEXT I
1033  GOSUB 8100
1034  CALL  - 32653: FOR I = 1 TO 4 * K: CALL  - 32695: NEXT I
1035  GOSUB 8360
1036  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1037  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1040  CALL  - 32653
1041  FOR I = 1 TO 10 * K: CALL  - 32667: NEXT I: GOSUB 1900: CALL  - 32653
1042  FOR I = 1 TO K: CALL  - 32667: NEXT I
1043  GOSUB 8330
1044  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1050  CALL  - 32653
1052  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1054  GOSUB 1900
1055  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1056  GOSUB 8300
1057  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1060  CALL  - 32653
1062  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1064  GOSUB 1900
1065  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1066  GOSUB 8280
```

```
1067  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1070  CALL  - 32653
1072  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1074  GOSUB 1900
1075  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1076  GOSUB 8250
1077  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1080  CALL  - 32653
1082  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1084  GOSUB 1900
1085  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1086  GOSUB 8220
1087  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1090  CALL  - 32653
1092  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1094  GOSUB 1900
1095  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1096  GOSUB 8180
1097  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1100  CALL  - 32653
1102  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1104  GOSUB 1900
1105  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1106  GOSUB 8150
1107  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1110  CALL  - 32653
1112  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1114  GOSUB 1900
1115  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1116  GOSUB 8120
1117  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1120  CALL  - 32653
1122  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1124  GOSUB 1900
1125  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1126  GOSUB 8100
1127  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1130  CALL  - 32653: FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1899  RETURN
1900  REM  X-AXIS MARKINGS
1910  CALL  - 32653
1914  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
1916  CALL  - 32646
1918  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
1920  CALL  - 32653
1922  FOR I = 1 TO 6 * K: CALL  - 32681: NEXT I
1999  RETURN
2000  REM  Y-AXIS
2014  CALL  - 32646
2016  FOR I = 1 TO 70 * K: CALL  - 32712: NEXT I
2020  GOSUB 2900
2030  GOSUB 8280
2035  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2040  FOR I = 1 TO 8 * K: CALL  - 32681: NEXT I
2042  GOSUB 2900
2044  GOSUB 8250
2045  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2050  FOR I = 1 TO 8 * K: CALL  - 32681: NEXT I
2052  GOSUB 2900
2054  GOSUB 8220
2055  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2060  FOR I = 1 TO 8 * K: CALL  - 32681: NEXT I
2062  GOSUB 2900
2064  GOSUB 8180
2065  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2070  FOR I = 1 TO 8 * K: CALL  - 32681: NEXT I
```

LISTING 5.2 (*Continued*)

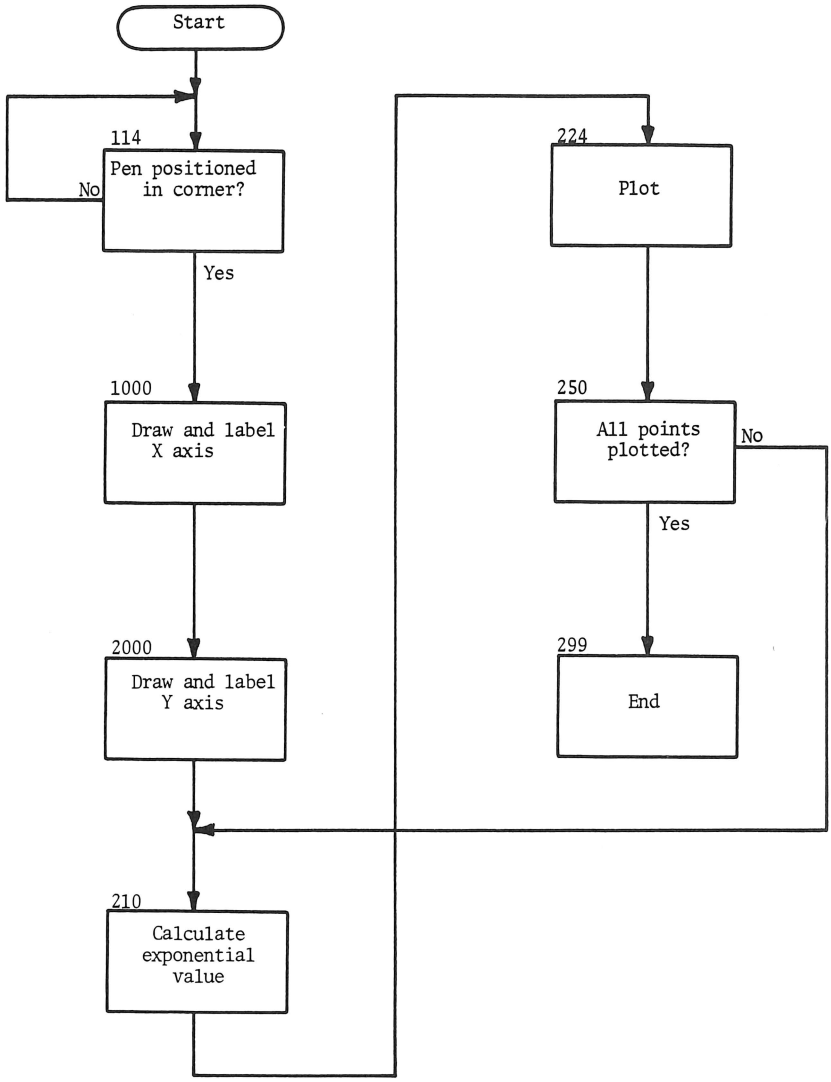
```
2072  GOSUB 2900
2074  GOSUB 8150
2075  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2080  FOR I = 1 TO 8 * K: CALL  - 32681: NEXT I
2082  GOSUB 2900
2084  GOSUB 8120
2085  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2090  FOR I = 1 TO 8 * K: CALL  - 32681: NEXT I
2092  GOSUB 2900
2094  GOSUB 8100
2095  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2100  FOR I = 1 TO 8 * K: CALL  - 32681: NEXT I
2899  RETURN
2900  REM  Y-AXIS MARKINGS
2910  CALL  - 32653
2914  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
2916  CALL  - 32646
2918  FOR I = 1 TO 4 * K: CALL  - 32667: NEXT I
2920  CALL  - 32653
2922  FOR I = 1 TO 4 * K: CALL  - 32667: NEXT I
2924  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
2999  RETURN
8000  REM  NUMERIC SUBROUTINES
8100  REM  "1"
8101  CALL  - 32646
8102  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8104  FOR I = 1 TO K: CALL  - 32667: NEXT I
8106  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8108  FOR I = 1 TO K: CALL  - 32674: NEXT I
8110  CALL  - 32653: FOR I = 1 TO K: CALL  - 32702: NEXT I
8112  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8114  FOR I = 1 TO K: CALL  - 32667: NEXT I
8116  RETURN
8120  REM  "2"
8122  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8123  CALL  - 32646
8124  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8126  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
8128  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8130  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
8132  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8134  CALL  - 32653
8136  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8138  RETURN
8150  REM  "3"
8152  CALL  - 32653
8154  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
8156  CALL  - 32646
8158  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8160  CALL  - 32653
8162  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8164  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
8166  CALL  - 32646
8168  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8170  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8172  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8174  RETURN
8180  REM  "4"
8182  CALL  - 32653
8184  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8186  CALL  - 32646
8188  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
8190  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8192  CALL  - 32646
```

```
8194  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
8196  CALL  - 32646
8198  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8200  CALL  - 32653
8210  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8212  RETURN
8220  REM  "5"
8222  CALL  - 32653
8224  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8226  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8228  CALL  - 32646
8230  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8232  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
8234  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8236  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
8238  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8240  RETURN
8250  REM  "6"
8252  CALL  - 32653
8254  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
8256  CALL  - 32646
8258  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8260  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
8262  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8264  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8266  CALL  - 32653
8268  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8270  RETURN
8280  REM  "7"
8282  CALL  - 32653
8284  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8286  CALL  - 32646
8288  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8290  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8292  CALL  - 32653
8294  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8296  RETURN
8300  REM  "8"
8302  CALL  - 32646
8304  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8306  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8308  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8310  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8312  CALL  - 32653
8314  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
8316  CALL  - 32646
8318  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8320  CALL  - 32653
8322  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8324  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
8326  RETURN
8330  REM  "9"
8332  CALL  - 32653
8334  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
8336  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8338  CALL  - 32646
8340  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8342  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
8344  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8346  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8348  CALL  - 32653
8350  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8352  RETURN
8360  REM  "0"
8362  CALL  - 32646
8364  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
```

LISTING 5.2 (*Continued*)

```
8366  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8368  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8370  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8372  RETURN
10000  DATA    160,9,24,72,176,7,169,0,141,209,192,144,5,169,1,141,209,192,169,3
10002  DATA  72,169,4,74,144,253,104,233,1,208,245,104,106,136,208,223,160,2,169
10004  DATA    1,141,209,192,169,3,72,169,4,74,144,253,104,233,1,208,245,136,208
10006  DATA  235,96,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
10008  DATA  72,8,169,112,32,224,127,40,104,96,72,8,169,113,76,60,128,72,8,169,114
10010  DATA  76,60,128,72,8,169,115,76,60,128,72,8,169,116,76,60,128,72,8,169,117
10012  DATA  76,60,128,72,8,169,118,76,60,128,72,8,169,119,76,60,128,72,8,169,121
10014  DATA  76,60,128,72,8,169,122,76,60,128
```

FIGURE 5.4 Flow chart for the digital plotter program.



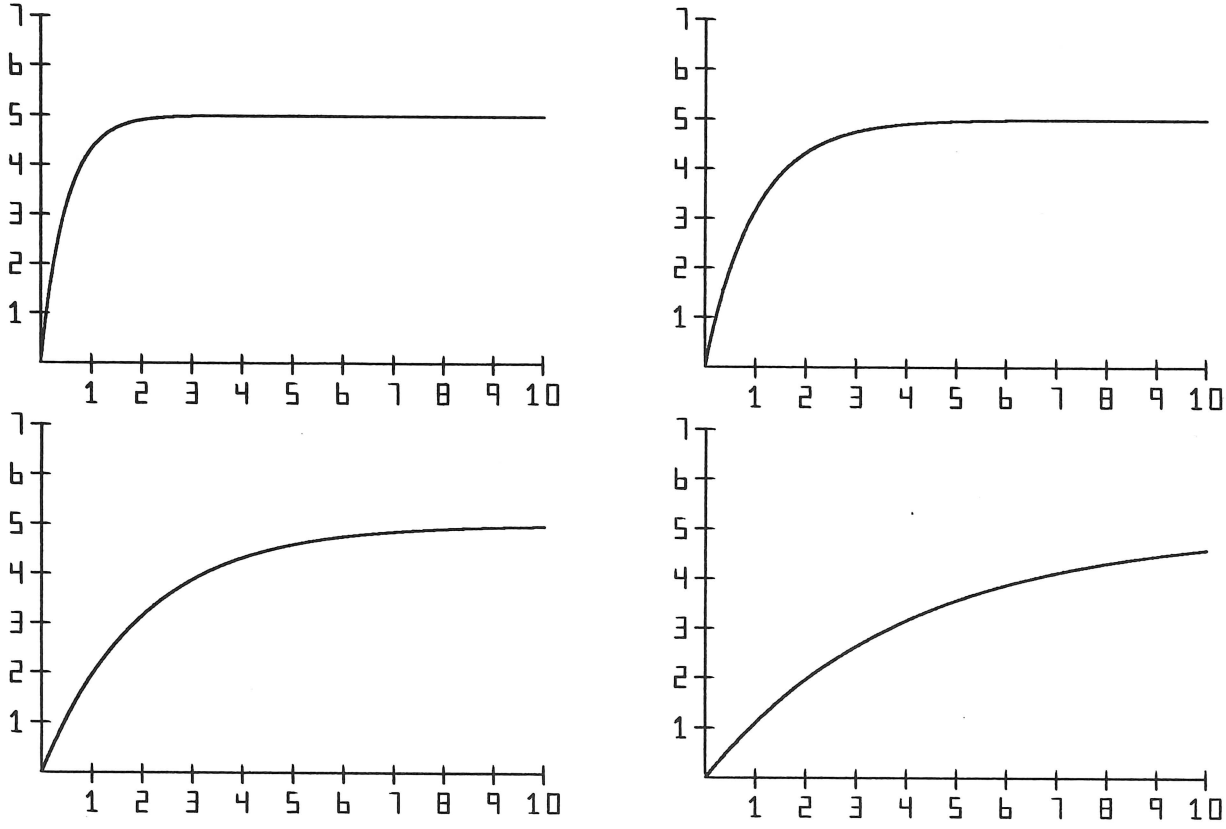


FIGURE 5.5 Series of exponential plots for increasing values of the time constant.

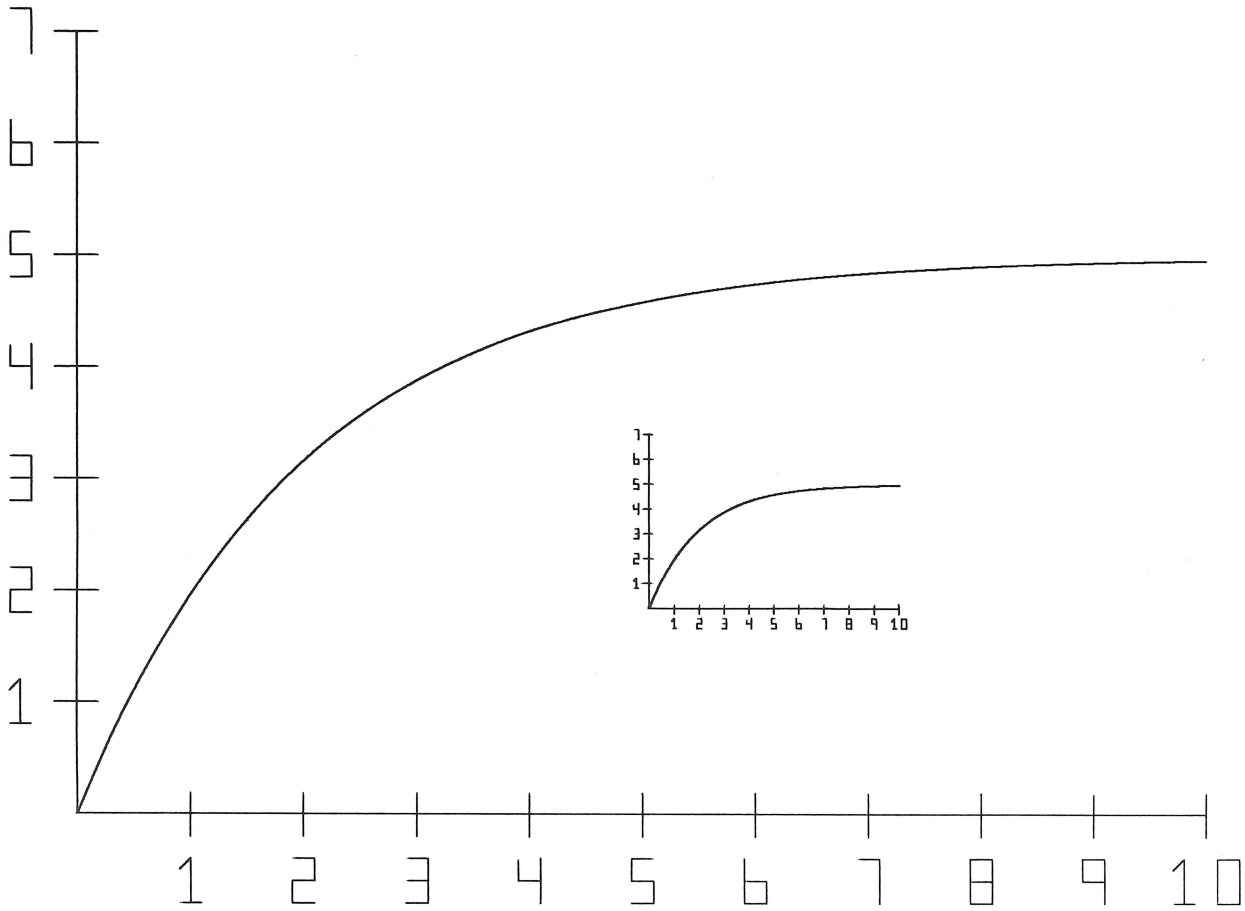


FIGURE 5.6 Maximum and minimum plot dimensions.

to make it easier for the reader to follow. Consequently, a significant increase in plotting speed can be realized by reducing the number of subroutine calls and keeping the software compacted as much as is possible.

Suppose we would like to plot some of the data that we digitized with the high speed A/D converter and stored on disk back in Chapter 3. Listing 5.3 shows a program which will take the stored data and plot it on the digital plotter. Figure 5.7 shows a plot of a sine wave plotted at both the the maximum and minimum plot size. The frequency of the sine wave was approximately 10 Hz. You should be aware that the horizontal scale (for a sampling rate of 1000 samples per second) is such that one period of a 20 Hz sine would occupy one inch. Figure 5.8 shows a plot of digitized music which was playing on the radio while I wrote this. Note that it is very difficult to say much about the frequency content of the music from the plot. When you get to Chapter 8, I will show you how you can analyze data similar to this and come to some conclusions about the frequency spectrum.

LISTING 5.3 BASIC program for plotting data stored on a disc.

```
10  REM  DIGITAL PLOTTER
12  REM  APPLE II
14  REM  R. HALLGREN     9-15-81
16  HIMEM: 30000
20  FOR I = 0 TO 160: READ K
22  POKE ( - 32800 + I),K
24  NEXT I
100  REM  MAIN PROGRAM
110  HOME : VTAB 12
112  PRINT "POSITION PEN IN LOWER LEFT HAND"
114  PRINT "CORNER. PRESS ANY KEY TO CONTINUE."
116  GET A$
118  HOME
120  PRINT "INPUT THE SCALE FACTOR (3<K<18)"
122  INPUT K
124  IF K < 4 OR K > 17 THEN  GOTO 118
128  HOME
140  GOSUB 1000
150  GOSUB 2000
200  REM  PLOT DEMONSTRATION
202  DIM X1(2048):D$ = ""
203  PRINT D$;"BLOAD DATA($1100),A$6100"
205 X = 25136
206  FOR Z = 0 TO 2047:X = X + 2
208 V1 =  PEEK (X):V2 =  PEEK (X + 1)
209  IF V1 > 1 THEN  GOTO 218
210 X1(Z) =  - ((511 - (V1 * 256 + V2)) / 100)
211  NEXT Z
212  GOTO 220
218 X1(Z) = (((V1 - 2) * 256 + V2) / 100)
219  GOTO 211
220  RESTORE : FOR I = 0 TO 160: READ R
221  POKE ( - 32800 + I),R: NEXT I
```

LISTING 5.3 (*Continued*)

```
222 Z = 0: CALL  - 32646: FOR I = 0 TO 100 * K:L =  INT (10 * K * X1(I))
224  IF L - Z = 0 THEN  GOTO 250: REM  NO CHANGE IN POTENTIAL
226  IF L - Z < 0 THEN  GOTO 240: REM  POTENTIAL IS DECREASING
228  FOR J = 1 TO (L - Z): REM  POTENTIAL IS INCREASING
230  CALL  - 32712
232  NEXT J
234  GOTO 248
240  FOR J = 1 TO (Z - L)
242  CALL  - 32681: NEXT J: REM  MOVE PEN IN -Y DIRECTION
248 Z = L
250  CALL  - 32695: NEXT I: REM                MOVE PEN IN +X DIRECTION
299  END
1000  REM  X-AXIS
1010  CALL  - 32653
1012  FOR I = 1 TO 675 + 3 * K: CALL  - 32712: NEXT I
1013  FOR I = 1 TO K + 90: CALL  - 32695: NEXT I
1014  CALL  - 32646
1016  FOR I = 1 TO 100 * K: CALL  - 32695: NEXT I
1020  GOSUB 1900
1030  CALL  - 32653
1032  FOR I = 1 TO 3 * K: CALL  - 32667: NEXT I
1033  GOSUB 8100
1034  CALL  - 32653: FOR I = 1 TO 4 * K: CALL  - 32695: NEXT I
1035  GOSUB 8360
1036  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1037  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1040  CALL  - 32653
1041  FOR I = 1 TO 10 * K: CALL  - 32667: NEXT I: GOSUB 1900: CALL  - 32653
1042  FOR I = 1 TO K: CALL  - 32667: NEXT I
1043  GOSUB 8330
1044  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1050  CALL  - 32653
1052  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1054  GOSUB 1900
1055  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1056  GOSUB 8300
1057  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1060  CALL  - 32653
1062  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1064  GOSUB 1900
1065  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1066  GOSUB 8280
1067  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1070  CALL  - 32653
1072  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1074  GOSUB 1900
1075  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1076  GOSUB 8250
1077  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1080  CALL  - 32653
1082  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1084  GOSUB 1900
1085  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1086  GOSUB 8220
1087  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1090  CALL  - 32653
1092  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1094  GOSUB 1900
1095  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1096  GOSUB 8180
1097  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1100  CALL  - 32653
1102  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1104  GOSUB 1900
```

```
1105  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1106  GOSUB 8150
1107  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1110  CALL  - 32653
1112  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1114  GOSUB 1900
1115  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1116  GOSUB 8120
1117  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1120  CALL  - 32653
1122  FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1124  GOSUB 1900
1125  CALL  - 32653: FOR I = 1 TO K: CALL  - 32667: NEXT I
1126  GOSUB 8100
1127  CALL  - 32653: FOR I = 1 TO 8 * K: CALL  - 32712: NEXT I
1130  CALL  - 32653: FOR I = 1 TO 9 * K: CALL  - 32667: NEXT I
1899  RETURN
1900  REM  X-AXIS MARKINGS
1910  CALL  - 32653
1914  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
1916  CALL  - 32646
1918  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
1920  CALL  - 32653
1922  FOR I = 1 TO 6 * K: CALL  - 32681: NEXT I
1999  RETURN
2000  REM  Y-AXIS
2014  CALL  - 32646
2016  FOR I = 1 TO 40 * K: CALL  - 32712: NEXT I
2020  GOSUB 2900
2030  GOSUB 8180
2035  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2040  FOR I = 1 TO 8 * K: CALL  - 32681: NEXT I
2042  GOSUB 2900
2044  GOSUB 8150
2045  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2050  FOR I = 1 TO 8 * K: CALL  - 32681: NEXT I
2052  GOSUB 2900
2054  GOSUB 8120
2055  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2060  FOR I = 1 TO 8 * K: CALL  - 32681: NEXT I
2062  GOSUB 2900
2064  GOSUB 8100
2065  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2070  FOR I = 1 TO 18 * K: CALL  - 32681: NEXT I
2072  GOSUB 2900
2074  GOSUB 8100
2075  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2080  FOR I = 1 TO 8 * K: CALL  - 32681: NEXT I
2082  GOSUB 2900
2084  GOSUB 8120
2085  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2090  FOR I = 1 TO 8 * K: CALL  - 32681: NEXT I
2092  GOSUB 2900
2094  GOSUB 8150
2095  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2100  FOR I = 1 TO 8 * K: CALL  - 32681: NEXT I
2110  GOSUB 2900
2112  GOSUB 8180
2114  CALL  - 32653: FOR I = 1 TO 6 * K: CALL  - 32695: NEXT I
2116  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
2120  CALL  - 32646
2122  FOR I = 1 TO 40 * K: CALL  - 32712: NEXT I
2899  RETURN
2900  REM  Y-AXIS MARKINGS
2910  CALL  - 32653
2914  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
```

LISTING 5.3 (*Continued*)

```
2916  CALL  - 32646
2918  FOR I = 1 TO 4 * K: CALL  - 32667: NEXT I
2920  CALL  - 32653
2922  FOR I = 1 TO 4 * K: CALL  - 32667: NEXT I
2924  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
2999  RETURN
8000  REM  NUMERIC SUBROUTINES
8100  REM  "1"
8101  CALL  - 32646
8102  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8104  FOR I = 1 TO K: CALL  - 32667: NEXT I
8106  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8108  FOR I = 1 TO K: CALL  - 32674: NEXT I
8110  CALL  - 32653: FOR I = 1 TO K: CALL  - 32702: NEXT I
8112  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8114  FOR I = 1 TO K: CALL  - 32667: NEXT I
8116  RETURN
8120  REM  "2"
8122  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8123  CALL  - 32646
8124  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8126  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
8128  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8130  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
8132  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8134  CALL  - 32653
8136  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8138  RETURN
8150  REM  "3"
8152  CALL  - 32653
8154  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
8156  CALL  - 32646
8158  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8160  CALL  - 32653
8162  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8164  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
8166  CALL  - 32646
8168  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8170  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8172  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8174  RETURN
8180  REM  "4"
8182  CALL  - 32653
8184  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8186  CALL  - 32646
8188  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
8190  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8192  CALL  - 32646
8194  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
8196  CALL  - 32646
8198  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8200  CALL  - 32653
8210  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8212  RETURN
8220  REM  "5"
8222  CALL  - 32653
8224  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8226  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8228  CALL  - 32646
8230  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8232  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
8234  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
```

```
8236  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
8238  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8240  RETURN
8250  REM  "6"
8252  CALL  - 32653
8254  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
8256  CALL  - 32646
8258  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8260  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
8262  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8264  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8266  CALL  - 32653
8268  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8270  RETURN
8280  REM  "7"
8282  CALL  - 32653
8284  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8286  CALL  - 32646
8288  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8290  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8292  CALL  - 32653
8294  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8296  RETURN
8300  REM  "8"
8302  CALL  - 32646
8304  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8306  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8308  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8310  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8312  CALL  - 32653
8314  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
8316  CALL  - 32646
8318  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8320  CALL  - 32653
8322  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8324  FOR I = 1 TO 2 * K: CALL  - 32681: NEXT I
8326  RETURN
8330  REM  "9"
8332  CALL  - 32653
8334  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
8336  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8338  CALL  - 32646
8340  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8342  FOR I = 1 TO 2 * K: CALL  - 32712: NEXT I
8344  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8346  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8348  CALL  - 32653
8350  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8352  RETURN
8360  REM  "0"
8362  CALL  - 32646
8364  FOR I = 1 TO 4 * K: CALL  - 32712: NEXT I
8366  FOR I = 1 TO 2 * K: CALL  - 32695: NEXT I
8368  FOR I = 1 TO 4 * K: CALL  - 32681: NEXT I
8370  FOR I = 1 TO 2 * K: CALL  - 32667: NEXT I
8372  RETURN
10000  DATA    160,9,24,72,176,7,169,0,141,209,192,144,5,169,1,141,209,192,169,3
10002  DATA  72,169,4,74,144,253,104,233,1,208,245,104,106,136,208,223,160,2,169
10004  DATA    1,141,209,192,169,3,72,169,4,74,144,253,104,233,1,208,245,136,208
10006  DATA  235,96,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
10008  DATA  72,8,169,112,32,224,127,40,104,96,72,8,169,113,76,60,128,72,8,169,114
10010  DATA  76,60,128,72,8,169,115,76,60,128,72,8,169,116,76,60,128,72,8,169,117
10012  DATA  76,60,128,72,8,169,118,76,60,128,72,8,169,119,76,60,128,72,8,169,121
10014  DATA  76,60,128,72,8,169,122,76,60,128
```

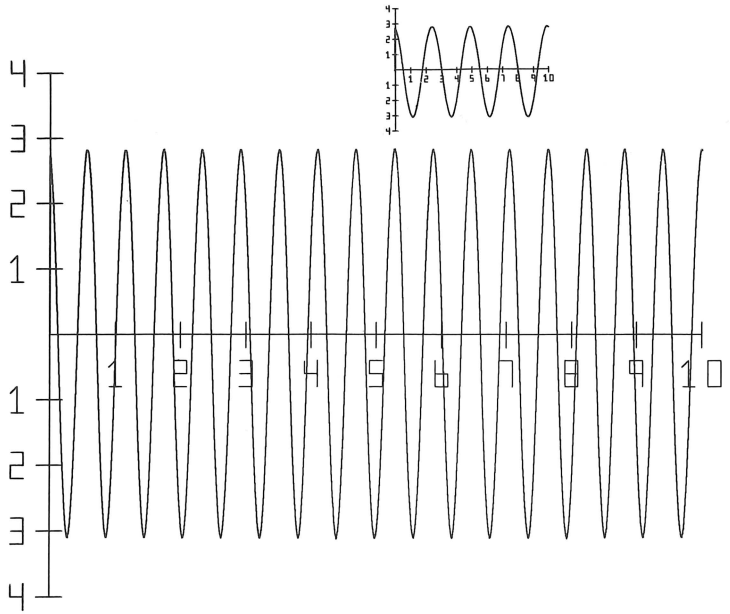


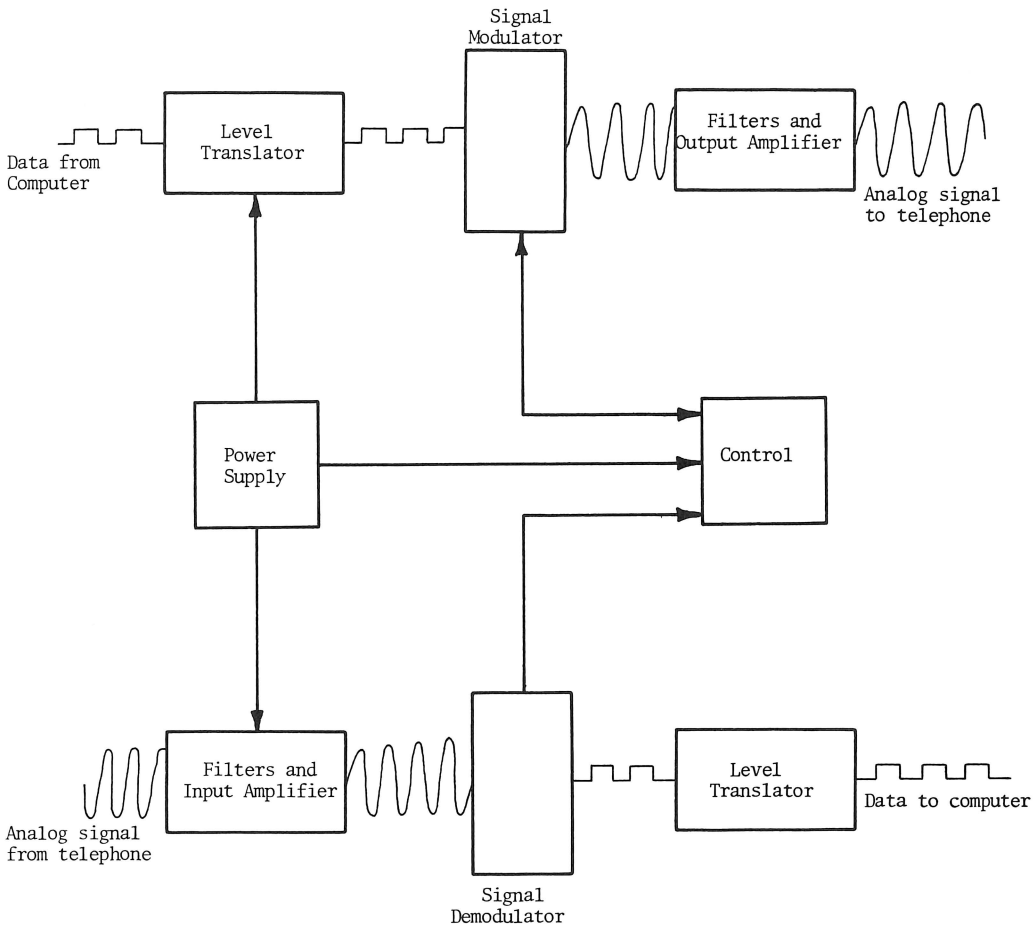
FIGURE 5.7 Sine wave (10 Hz) digitized at 1000 samples per second.

FIGURE 5.8 Music digitized at 1000 samples per second.

VIDEO TERMINAL

There will be times when you will want to use your Apple II as a video terminal to connect into a large, host computer network. Networks that provide a message retrieval system have been around for quite a while, and we are now beginning to see a proliferation of information services which provide local, national, and international news, weather, sports, and investment-related topics. In the future, you will probably have access to information suppliers dealing with banking, car rental, classified ads, and reservation services. Individuals usually have access to one of these networks through the use of a modem connected between a video terminal and their telephone. A modem is a device which performs two basic functions (see Figure 5.9):

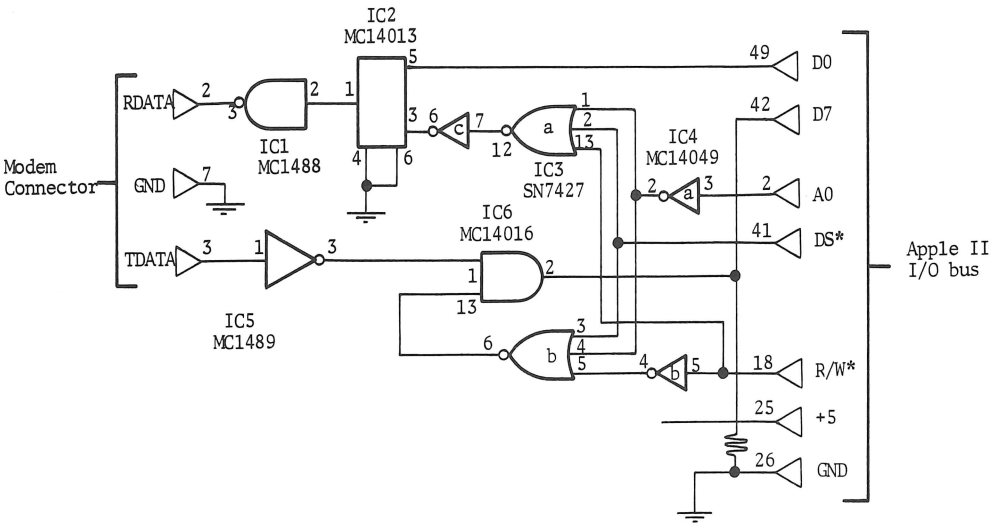
FIGURE 5.9 Block diagram of a modem.



1. It accepts digital input from a computer and converts the pulses into analog-frequency signals for transmission over the telephone lines.
2. It converts analog-frequency signals from the telephone into digital signals which the computer can process.

Modems that transmit information at 300 bits per second are readily available through a multitude of suppliers for under $200. You can use the Apple II as a video terminal by building a bidirectional serial interface and writing some software. You could accomplish the same thing by buying a commercial serial interface board, but you can save a few dollars by building your own. You should realize that my approach minimizes hardware and maximizes software, thus saving money at the expense of versatility. Figure 5.10 shows the hardware that will be needed, and the connections that will need to be made to the Apple II and to the

FIGURE 5.10 Video terminal interface circuit and system connections.



Number	Type	+5	+12	-12	GND
IC1	MC1488	--	14	1	7
IC2	MC14013	14	--	--	7
IC3	SN7427	14	--	--	7
IC4	MC14049	1	--	--	8
IC5	MC1489	14	--	--	7
IC6	MC14016	14	--	--	7

modem. You should recognize the circuits as ones that were developed and described in Chapter 2. Once you have constructed the interface and made the interconnections, perform the following tests to make sure that everything is working correctly:

1. If you execute the following BASIC statement the output of IC1 should go to +10 volts.
   POKE −16143,0
2. If you execute the following BASIC statement the output of IC1 should go to −10 volts.
   POKE −16143,1
3. If you execute the following BASIC statements the number which will be displayed on the video monitor should change from a 1 to a 0 when you apply +5 volts to the SERIAL INPUT line.
   100K= PEEK (−16143)
   110 IF K<128 THEN PRINT "0"
   120 IF K>128 THEN PRINT "1"
   130 GOTO 100

Listing 5.4 shows the machine language program (see Figure 5.11 for the program flow chart) which allows the Apple II to transmit and receive serial data at 300 bits per second. Listing 5.5 shows the program converted over to a series of BASIC statements.

LISTING 5.4 Machine language routine for the bi-direction serial interface.

```
300    AD 00 C0     LDA  $C000     SAMPLE KEYBOARD
303    48           PHA            SAVE A REGISTER
304    C9 80        CMP  #$80      CHECK FOR CHARACTER
306    30 38        BMI  $340      JUMP TO RECEIVE
308    A9 00        LDA  #$00
30A    8D 10 00     STA  $C010     RESET KEYBOARD
30D    68           PLA            RESTORE A REGISTER
30E    29 7F        AND  #$7F
310    A0 0B        LDY  #$0B      11 BITS
312    18           CLC            CLEAR CARRY
313    48           PHA            SAVE A REGISTER
314    B0 07        BCS  $31D      MARK
316    A9 00        LDA  #$00
318    8D F1 C0     STA  $C0F1     SEND SPACE
31B    90 05        BCC  $322
31D    A0 01        LDA #$01
31F    8D F1 C0     STA $C0F1      SEND MARK
322    20 30 03     JSR $330       JUMP TO DELAY
325    68           PLA            RESTORE A REGISTER
326    6A           ROR            GET NEXT BIT
327    88           DEY            ALL BITS SENT
328    D0 E9        BNE  $313      JUMP IF NOT
32A    4C 40 03     JMP  $340      JUMP TO RECEIVE
32D    EA           NOP
32E    EA           NOP
```

LISTING 5.4 (*Continued*)

```
32F    EA          NOP
330    A9 4D       LDA  #$4D     LOAD A REGISTER
332    48          PHA           SAVE A REGISTER
333    A9 20       LDA  #$20     LOAD REGISTER
335    4A          LSR           SHIFT RIGHT
336    90 FD       BCC  $335     JUMP IF NOT ZERO
338    68          PLA           RESTORE A REGISTER
339    E9 01       SBC  #$01     SUBTRACT ONE
33B    D0 F5       BNE  $332     JUMP IF NOT ZERO
33D    60          RTS           RETURN
33E    EA          NOP
33F    EA          NOP
340    A9 00       LDA  #$00     LOAD A REGISTER
342    8D 80 03    STA  $380     TEMP A REGISTER
345    A2 08       LDX  #$08     8 DATA BITS
347    AD F1 C0    LDA  $C0F1    GET RECEIVED CHARACTER
34A    2A          ROL           ROTATE LEFT
34B    B0 B3       BCS  $300     JUMP TO SEND
34D    A9 26       LDA  #$26     1/2 CHARACTER DELAY
34F    48          PHA
350    A9 20       LDA  #$20
352    4A          LSR
353    90 FD       BCC  $352
355    68          PLA
356    E9 01       SBC  #$01
358    D0 F5       BNE  $34F
35A    20 30 03    JSR  $330     JUMP TO DELAY
35D    AD F1 C0    LDA  $C0F1    GET CHARACTER
360    29 80       AND  #$80     GET MSB
362    0D 80 03    ORA  $380     OR A REGISTER WITH TEMP
365    8D 80 03    STA  $380     SAVE IN TEMP
368    18          CLC           CLEAR CARRY
369    6E 80 03    ROR  $380     ROTATE TEMP RIGHT
36C    CA          DEX           ALL BITS RECEIVED?
36D    D0 EB       BNE  $35A     BRANCH IF NOT
36F    09 80       ORA  #$80     SET MSB
371    C9 C0       CMP  #$C0     CHECK FOR CONTROL CHARAC
373    F0 03       BEQ  $378     JUMP IF NOT
375    20 FD FB    JSR  $FBFD    DISPLAY ON VIDEO
378    20 30 03    JSR  $330     JUMP TO DELAY
37B    4C 00 03    JMP  $300     JUMP TO SEND
```

I will describe the startup procedure that I use for interacting with the university computer system. Since operating systems will differ from location to location, this should be used as an example only.

1. Load and execute the BASIC program.
2. Dial up the computer facility, listen for the carrier tone, and insert the handset into the modem (this assumes that you have not purchased a direct-connect modem).
3. Press the RETURN key. If the host does not respond, press the RETURN key again.
4. Once the host responds, sign on in the normal way.

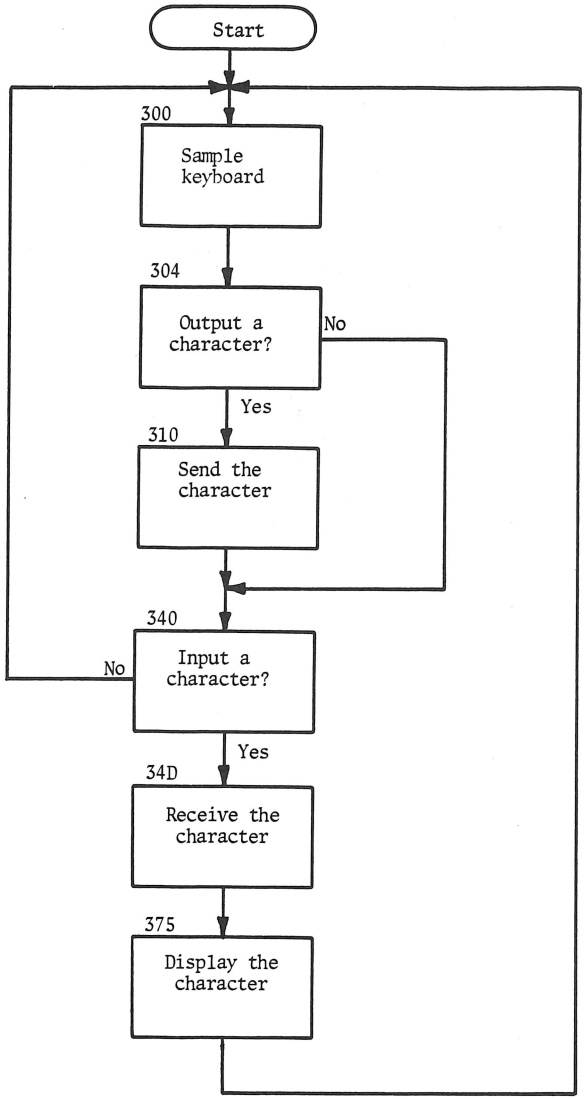


FIGURE 5.11 Video terminal program flow chart.

5. Limit the right hand margin to 38 characters to prevent losing data. Double the delay time before printing is resumed after a line feed and a carriage return to avoid losing characters.
6. To abort an operation, press the ESC key.

LISTING 5.5 The machine language program in Listing 5.4 incorporated into a BASIC program.

```
100 REM APPLE II VIDEO TERMINAL
110 REM R. HALLGREN, 9/17/81
120 FOR I=0 TO 125:READ K:POKE (768+I),K:NEXT I
126 HOME
128 PRINT "DIAL UP THE HOST COMPUTER AND PRESS THE
          'RETURN' KEY"
130 FOR I=1 TO 5:PRINT "":NEXT I
140 PRINT "REMEMBER TO LIMIT THE RIGHT MARGIN"
142 PRINT "TO 36 CHARACTERS, AND TO DOUBLE THE"
144 PRINT "DELAY THAT COMES AFTER A LINE FEED"
146 PRINT "AND A CARRIAGE RETURN."
150 CALL 773
199 END
10000 DATA 173,0,192,72,201,128,48,56,169,0,141,16,192,104,
          41,127,160,11,24,72
10002 DATA 176,7,169,0,141,241,192,144,5,169,1,141,241,192,
          32,48,3,104,106,136
10004 DATA 208,233,76,64,3,234,234,234,169,77,72,169,32,74,
          144,253,104,233,1
10006 DATA 208,245,96,234,234,169,0,141,128,3,162,8,173,
          241,192,42,176,179,169
10008 DATA 38,72,169,32,74,144,253,104,233,1,208,245,32,48,
          3,173,241,192,41,128
10010 DATA 13,128,3,141,128,3,24,110,128,3,202,208,235,9,
          128,201,192,240,3,32
10012 DATA 253,251,32,48,3,76,0,3
```

6

BIOFEEDBACK

Have you ever thought about the number of complex operations that your body is required to perform in the course of a "normal" day of activity? While we often take for granted our ability to perform complex, coordinated muscular activity, this ability results from years of trial-and-error type training. An infant has very little muscular control over its body, and it develops this control by constantly practicing. Most of us have observed a young child learning how to walk; repetitiously standing, taking a few steps, and falling down.

The human brain is composed of billions of specialized cells called *neurons*. Neurons are designed to transmit information between peripheral sensory receptors and the brain, to analize this information, and to transmit commands, if necessary, back to muscles. For example, when you touch an object, there are sen-

sory receptors in the skin that send the brain coded information related to the temperature of the object. The brain then processes the information and decides what course of action should be taken. Coded information is then sent to the muscles in the hand and arm. The possible result is that the hand may be jerked back from a very hot object, or left in place if the object is cool.

The body is equipped with many similar neuromuscular pathways that never get developed because there is no common use for them. It is no big trick to learn how to wiggle your ears; you just spend some time in front of a mirror teaching yourself which nerves are connected to that particular set of muscles. The normal process of learning requires that *feedback* accompany the behavior pattern that is being established. That is, you normally expect to see, hear, or feel the results of a particular action. It is difficult to learn how to play the violin if you are deaf. The normal learning experience requires that auditory feedback accompany manipulation of the bow.

Many functions of the body, such as heart rate and skin temperture—long thought to be under exclusive control of the autonomic nervous system—have been found to be controllable. Training involuntary muscles is normally not possible, because we lack a natural feedback path to tell us how we are affecting the system. However, with the aid of sensitive electronic equipment, physiological changes that a person is normally incapable of sensing can be altered and controlled. Thus, the term *biofeedback* is used when a biological process is measured, and the results of the measurement are fed back to the individual. Through a training experience, the individual can learn to control phenomena such as heart rate and skin temperature.

SKIN TEMPERATURE

Heat is produced in the human body by muscular exercise, assimilation of food, and all the processes that contribute to the basal metabolic rate. Heat is lost to the surroundings through radiation, conduction, and vaporization of water in the nasal passages, and from the skin. Humans—and vertebrates in general—have multiple mechanisms for regulating heat loss so that the body remains at an almost constant temperature under

normal conditions. One of the primary mechanisms for heat regulation is through control of skin temperature. Skin temperature is controlled by regulating the amount of blood that is allowed to flow to the skin. Cold hands and feet are a common phenomena resulting from peripheral vasoconstriction, resulting from a sympathetic nervous system command to contract the smooth muscles lining peripheral blood vessels, thus reducing blood circulation and skin temperature at the extremities and conserving heat.

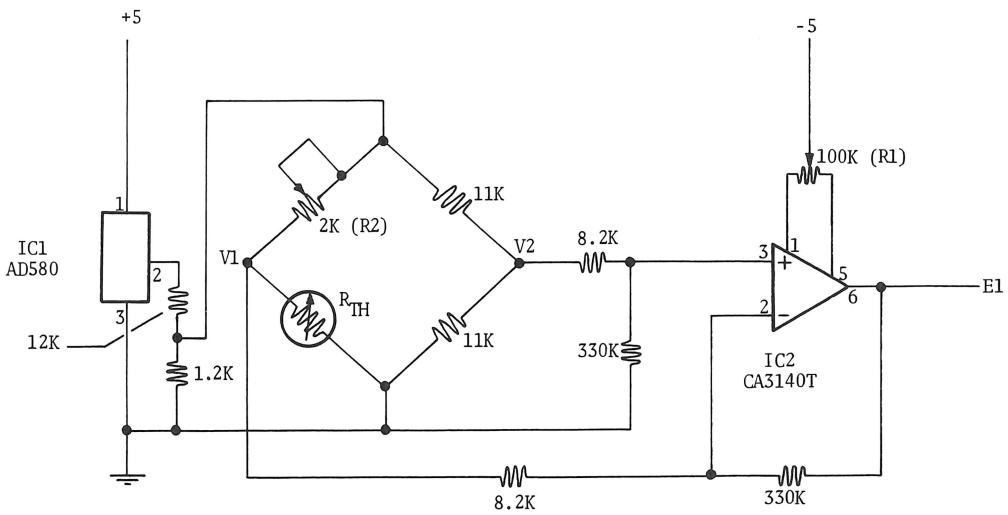
Peripheral skin temperature is influenced by a number of factors.

1. Stress causes fingertip temperature to drop several degrees below room temperature.
2. A variety of drugs, including tobacco, have an influence on vasoconstriction.
3. Vigorous activity increases peripheral circulation, while inactivity decreases circulation.

We will be using the low speed A/D converter that we developed in Chapter 3 along with an analog circuit to interface a thermistor to the Apple II. Figure 6.1 shows the schematic diagram of the

FIGURE 6.1 Schematic diagram of the analog circuitry for the biofeedback temperature monitor.

Number	Type	+5	-5	GND
IC1	AD580	1	--	3
IC2	CA3140T	7	4	--



analog circuitry. This design uses a thermistor, a device whose resistance is a function of its temperature, in one leg of a bridge circuit. Bridge circuits allow us to detect small changes in resistance by measuring imbalance in the bridge with a differential amplifier.

Thermistors are nearly ideal components mechanically. They are usually small in size, rugged, and they demonstrate the reliability and extended life common to semiconductor products. By using appropriate values of resistance in the bridge circuit, small changes in temperature can be made to produce large changes in output voltage. Since the output voltage is amplified by a differential amplifier (see Appendix B), there will be little problem of noise being introduced into the measurements.

Looking at Figure 6.1, IC1 is a voltage regulator which provides a stable reference voltage to the bridge circuitry. The output voltage from IC1 has been reduced to minimize temperature variations that might occur as a result of self-heating in the thermistor. Such variations, appearing as a slow drifting of the output signal, are undesirable. IC2 is a high gain, differential amplifier that is used to measure the difference between voltages V1 and V2.

Once you have built the analog circuit, you should make the following adjustments and voltage checks:

1. The voltage at pin 2 on IC1 should be equal to +2.5 volts.
2. Short the points labled V1 and V2 together and adjust R1 until the voltage at E1 is equal to 0 volts. This ensures that the output of the differential amplifier will be equal to 0 when the inputs are equipotential.
3. Remove the short from the points labled V1 and V2, hold the thermistor in your mouth for one minute, and adjust R2 (the temperature calibration adjustment) until the output voltage, E1, is equal to +1.07 volts. You should realize that we are going to be interested in relative changes in temperature and not in absolute values of temperature, so calibration will not be precisely performed.
4. Connect the output, E1, to the input of the A/D converter. Load and execute BASIC program 1 (see Listing 3.3). The video display should indicate that you are measuring a voltage that increases when you hold the thermistor between your fingertips and decreases when you let go of it.

5. Load and execute BASIC program 2 (see Listing 6.1 and Figure 6.2). You should see temperature plotted as each sample is taken. The plot should move toward the top of the screen for increases in temperature and toward the bottom of the screen for decreases in temperature. Figure 6.3 shows a data plot that results from first putting the thermistor into, and then taking the thermistor out of, the author's mouth. Notice how the temperature of the thermistor goes below the room temperature as a result of evaporation.

LISTING 6.1 BASIC program for biofeedback skin temperature experiments.

```
10  REM  LOWSPEED A/D CONVERTER #1
20  REM  R. HALLGREN,APPLE II,10-22-81
22  FOR I = 16384 TO 16586: READ D: POKE I,D: NEXT I
24  GOSUB 1000
30  REM  CONVERT ONE SAMPLE
32  HGR : HCOLOR= 3
34  HPLOT 0,0 TO 0,150: HPLOT  TO 270,150
40  FOR I = 1 TO 270
50  CALL 16384
70 X4 =  PEEK (18944):X3 =  PEEK (18945)
72 X2 =  PEEK (18946):X1 =  PEEK (18947)
73 W4 = X4
74  IF X4 > 7 THEN X4 = 0
75  IF X4 = 0 THEN  GOTO 80
76 X4 = 1
80 X$ =  STR$ (X4) +  STR$ (X3) +  STR$ (X2) +  STR$ (X1)
81 X =  -  VAL (X$) / 1000
82  IF X4 = 0 THEN W4 = W4 - 8
83  IF W4 > 3 THEN X =  - X
90  HPLOT I,(150 - 100 * X): FOR J = 0 TO 500: NEXT J: NEXT I
92  GOTO 30
99  END
1000  REM  INTRODUCTION
1010  HOME
1030  PRINT "THIS IS DEMONSTRATION PROGRAM FOR"
1032  PRINT "CONTROLLING SKIN TEMPERATURE USING"
1034  PRINT "BIOFEEDBACK IN CONJUNCTION WITH THE"
1036  PRINT "LOW SPEED A/D CONVERTER AND A DATA"
1038  PRINT "PLOT ROUTINE."
1040  PRINT "": PRINT ""
1042  PRINT "THE PROGRAM WILL PLOT A POINT EVERY": PRINT "SECOND"
1044  PRINT "": PRINT ""
1046  PRINT "PRESS THE SPACE BAR TO CONTINUE"
1050  GET K$
1052  IF K$ <  > " " THEN  GOTO 1050
1099  RETURN
2000  DATA  141,176,73,142,177,73,140,178,73,8,162,0,169,0,133
2002  DATA  10,169,74,133,11,76,64,64,0,0,0,0,0,0,0,0,0,0,0,0
2004  DATA  0,0,173,176,73,174,177,73,172,178,73,40,96
2006  DATA  234,234,234,234,234,234,234,234,234,234,234
2008  DATA  234,234,234,234,234,141,242,192,173,241,192
2010  DATA  41,128,201,128,208,247,173,240,192,141,162
2011  DATA  73,41,128,201,128,208,244,173
2012  DATA  162,73,41,15,129,10,164,10,200,132,10,208
2014  DATA  5,164,11,200,132,11,173,240,192,141,162,73
2016  DATA  41,64,201,64,208,244,173,162,73,41,15,129
2018  DATA  10,164,10,200,132,10,208,5,164,11,200,132
2020  DATA  11,173,240,192,141,162,73,41,32,201,32
2022  DATA  208,244,173,162,73,41,15,129,10,164,10
2024  DATA  200,132,10,208,5,164,11,200,132,11,173
2026  DATA  240,192,141,162,73,41,16,201,16,208,244
2028  DATA  173,162,73,41,15,129,10,164,10,200,132
2030  DATA  10,208,5,164,11,200,132,11,76,37,64
```

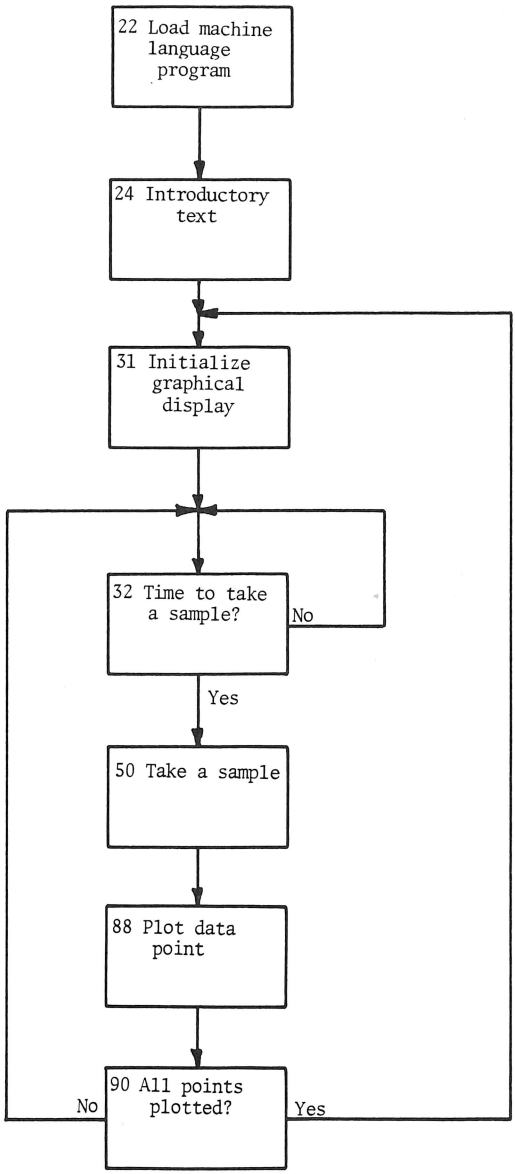


FIGURE 6.2 Flow chart of the BASIC program.

Figure 6.4 shows a diagrammatic representation of the experimental setup. You should tape the thermistor to the index finger on your dominant hand (the hand you write with). You will "see" temperature changes which are too small for you to detect, but

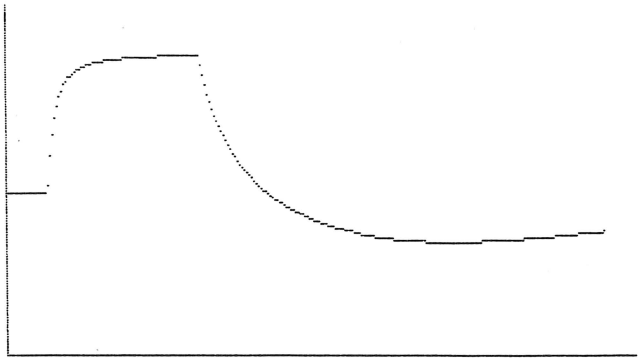
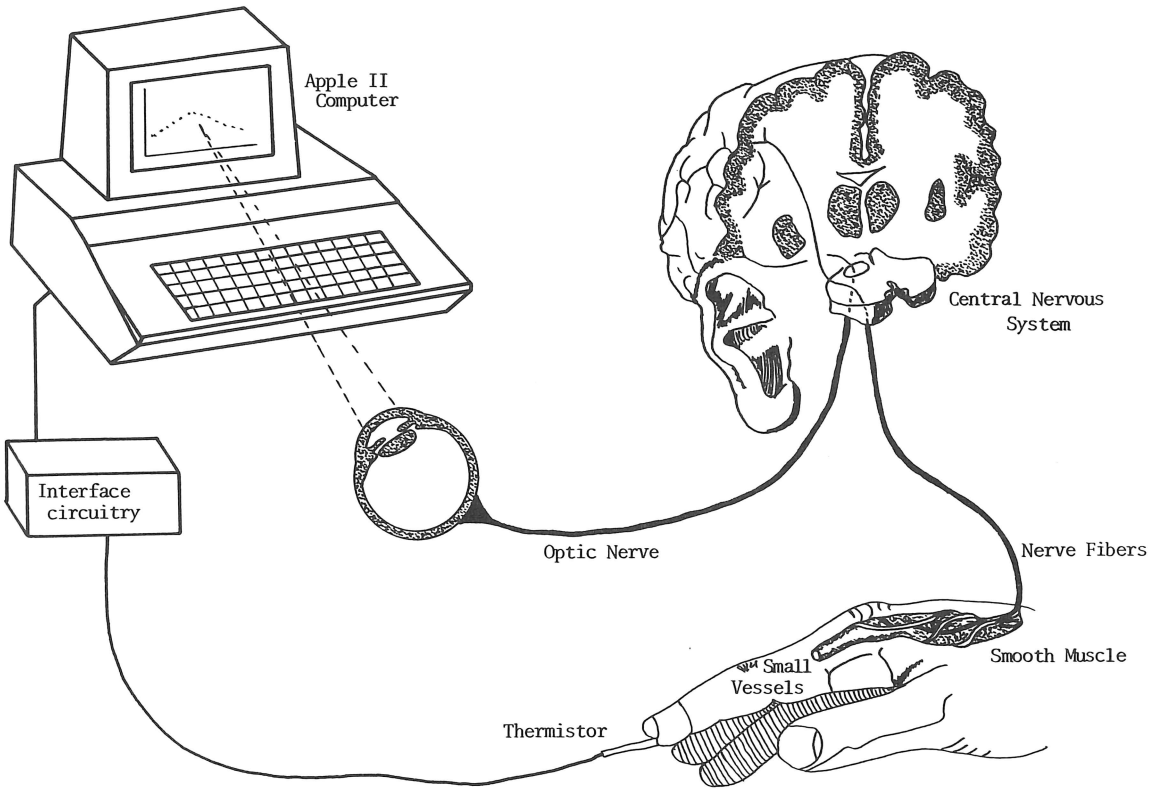


FIGURE 6.3 Graphic display resulting from placing the thermistor in the author's mouth and then removing it.

FIGURE 6.4 Diagrammatic representation of temperature feedback. The electronic measuring system informs the subject of temperature changes so small that they are normally not sensed.



which are easily detected by the thermistor. The graphic display on the CRT will serve as the feedback link to your central nervous system.

First seat yourself in a comfortable chair and, once you are relaxed, imagine that your hand has been placed in hot water. With some practice, you should be able to precisely control an increase or decrease in temperature. Within a few minutes you should be able to raise or lower your temperature one or two degrees merely by "telling" yourself to raise or lower your finger temperature. After some practice, you should be able to increase that variation to ten degrees.

You may want to monitor your temperature while watching a television program, or try taping the thermistor to another part of your body—such as your face—to see how vasoconstriction affects skin temperature in different locations.

HEART RATE

Heart rate changes as a function of many factors. Emotions such as anger and excitement cause an increase in heart rate. Emotions such as fear and grief cause a decrease in heart rate. The body has several regulatory mechanisms which monitor the concentration of carbon dioxide in the blood and the distention of blood vessels, and adjust heart rate to maintain cardiovasular system parameters within acceptable limits. We normally do not think of regulating our heart rate, primarily because there is not an obvious pathway for feedback. However, we can use an electronic measuring system to allow us to monitor our heart rate and to allow us to investigate normal responses to such things as breathing and relaxation.

We can conveniently get an indirect measurement of heart rate by using a system called *photoplethysmography*. Light can easily be transmitted through capillary beds existing in the earlobe or the fingertip. As arterial pulsations cause the blood volume in the capillary bed to increase and decrease, the amount of scattered, absorbed, and reflected light changes. This phenomena can be used to give us a signal which varies as a function of heart rate. Such a system is sensitive to motion artifacts and performs best when the subject is sitting quietly.

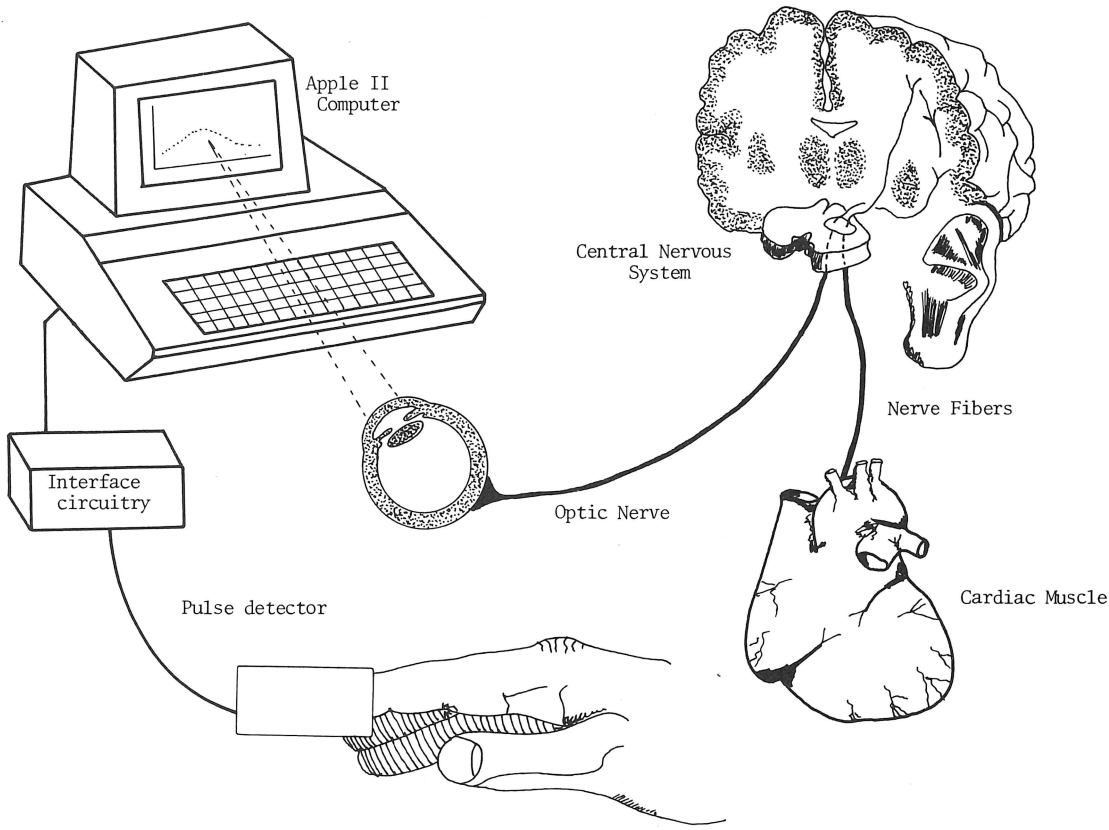
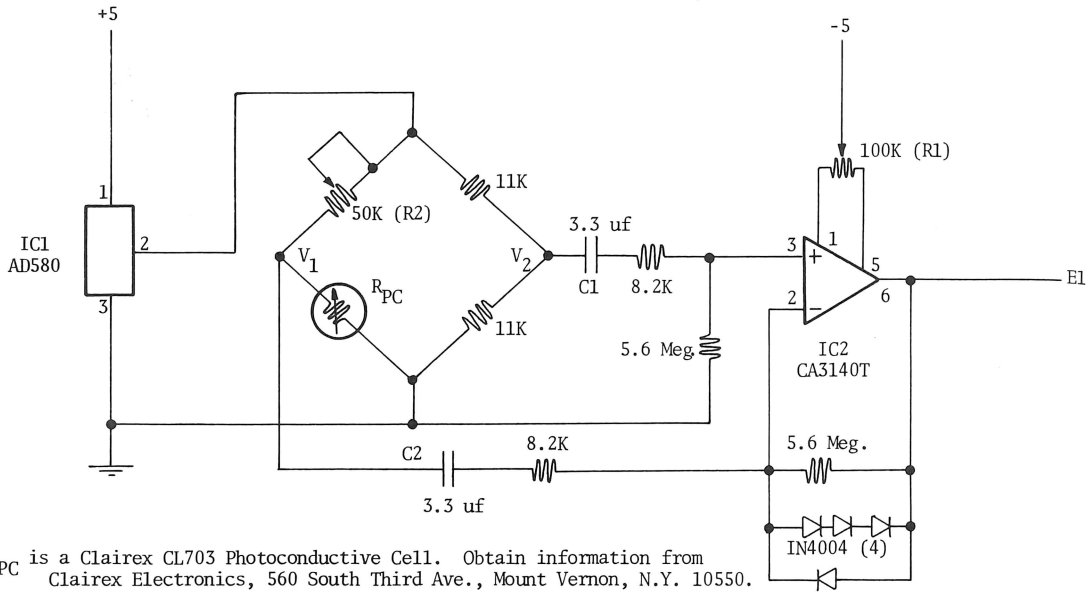


FIGURE 6.5 Diagrammatic representation of heart rate feedback. The electronic measuring system informs the subject of changes too small to be normally sensed.

Figure 6.5 shows a diagrammatic representation of the experimental setup. We will be using the capillary bed in your fingertip to monitor pulsations in blood volume due to contractions of the cardiac muscle. A pulse detector and an analog circuit will be used to detect, filter, and amplify the pulses so that they can be measured by the low speed A/D converter. The computer will then count the pulses and present your heart rate in the form of a graphic display.

Figure 6.6 shows a schematic diagram of the analog circuitry that we will use to interface the pulse detector to the low-speed A/D converter. You should notice that it is a modification of the circuit that we used for measuring skin temperature. This is primarily because a photocell, a device whose resistance changes

Number	Type	+5	-5	GND
IC1	AD580	1	--	3
IC2	CA3140T	7	4	--



R_{PC} is a Clairex CL703 Photoconductive Cell. Obtain information from Clairex Electronics, 560 South Third Ave., Mount Vernon, N.Y. 10550.

FIGURE 6.6 Schematic diagram of the analog circuitry for biofeedback heart rate monitor.

as a function of the intensity of light falling upon its surface, is being used to detect changes in light passing through the capillary bed in the finger. By putting the photocell into a bridge circuit, small changes in resistance that occur due to small changes in light intensity can be made to produce large changes in output voltage.

Looking at Figure 6.6, IC1 is a voltage regulator which provides a stable reference voltage to the bridge circuitry. Since we are counting pulses and not really measuring a value of resistance, we do not have to be overly concerned about output voltage drift due to internal heating of the photocell. Consequently, we do not have to reduce the output of the regulator, and can thus obtain increased sensitivity from the output of the bridge. IC2 is a high-gain, differential amplifier that is used to measure the difference between voltages V1 and V2. Capacitors C1 and C2 are included to

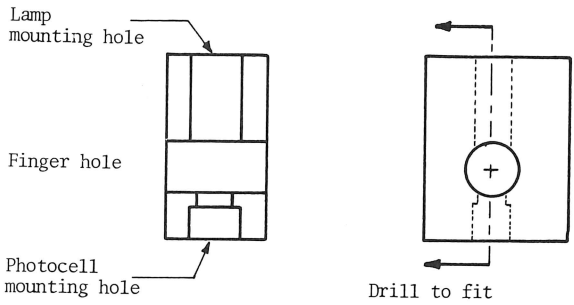


FIGURE 6.7a Position of the photocell relative to the lamp.

block the d.c. component of the amplifier to limit the output voltage, increasing the sharpness of the voltage change that occurs when the heart beats.

You should first concern yourself with the construction of the pulse detector. Figure 6.7a shows a drawing indicating the position of the photocell relative to the light source. The distance between the photocell and the light source will depend on the size of your fingers. To keep this distance to a minimum, make the hole just large enough to fit the smallest finger on your hand, usually the little finger. To get enough intensity from the lamp you will need a 3-volt d.c. supply that can provide about 250 milliamperes. You can use two D-cell batteries connected in series, or you can build a 5-volt supply from Appendix C and use a 10 ohm, 1 watt resistor in series with the lamp. I have shown the latter. To simplify construction as much as possible, I mounted the photocell and the lamp in a small block of wood.

Once you have built the pulse detector and the analog circuit, you should make the following adjustments and voltage checks:

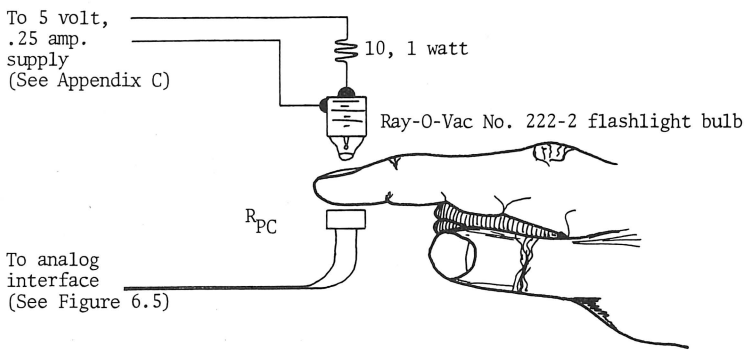
1. The voltage at pin 2 on IC1 should be equal to +2 volts.
2. Short the points labled V1 and V2 together and adjust R1 until the voltage at E1 is equal to 0 volts.
3. Remove the short from the points labeled V1 and V2, and connect the output, E1, to the input of the A/D converter. Load and execute BASIC program 3 (See Listing 6.2). With the lamp disconnected from the lamp supply, you should see the graphics display periodically flashing. When the lamp is connected to its power supply, the flashing should stop.
4. Because of the simplicity of the design, you are going to have to develop some skill in positioning your finger in the pulse detector

LISTING 6.2 BASIC program for biofeedback heart rate system set-up.

```
10  REM  BIOFEEDBACK; HEART RATE SYSTEM SET UP
20  REM  R. HALLGREN, APPLE II, 11-05-81
22  FOR I = 16384 TO 16458: READ D: POKE I,D: NEXT I
24  GOSUB 1000
200  REM  SAMPLE INTERFACE
210  HOME : VTAB 12
220  CALL 16384
230  PRINT "THROB"
232  FOR I = 1 TO 100: NEXT I
240  GOTO 200
1000  REM  DEMONSTRATION
1010  HOME
1020  PRINT "THIS PROGRAM WILL RESPOND TO THE PULSE"
1022  PRINT "DETECTOR OUTPUT.": PRINT ""
1024  PRINT "YOU WILL START THE TEST WITH THE LAMP": PRINT "TURNED OFF.":
      PRINT "": PRINT ""
1026  PRINT "AFTER DETERMINING THAT THE INTERFACE IS"
1028  PRINT "PERFORMING O.K., YOU WILL TURN ON THE"
1030  PRINT "LAMP AND SEE IF THE SOFTWARE IS O.K.": PRINT "": PRINT ""
1032  PRINT "PRESS THE SPACE BAR TO CONTINUE"
1034  GET K$: IF K$ < > " " THEN  GOTO 1034
1099  RETURN
10000  DATA  141,176,73,142,177,73,140,178,73,8,141,242,192,173,241,192,4
     1,128
10002  DATA  201,128,208,247,173,240,192,141,162,73,41,128,201,128,208,24
     4,173
10004  DATA    162,73,41,4,201,0,208,223,173,240,192,141,162,73,41,32,201
     ,32,208,244
10006  DATA       173,162,73,41,15,201,2,48,202,173,176,73,174,177,73,172
     ,178,73,40,96
```

to ensure consistent operation. We learned in the previous section that cold hands are a good indication of poor circulation. Poor circulation means that blood flow is reduced. This means that the signals from the pulse detector will be small, resulting in erratic operation. If your hands are cold, hold them under warm water for a few minutes. Now, insert your little finger into the pulse detector. Figure 6.7b shows the relative position of the finger with respect to the photocell. As you insert your finger, you should see the display

FIGURE 6.7b Position of the finger relative to the photocell.



flash in response to the motion of your finger. After you have settled down, you should see the graphics display periodically start to pulse in response to the beat of your heart. Your finger should rest lightly upon the face of the photocell. Too much pressure will stop circulation and cause the display to skip beats.

5. Load and execute the BASIC program 4 (See Listing 6.3, Listing 6.4, and Figure 6.8). The program should flash in response to each heart beat, and should display a graphical representation of pulse rate in beats per minute. Figure 6.9a shows a graphical display of the author's resting heart rate.

LISTING 6.3 BASIC program for biofeedback heart rate experiments.

```
10  REM   BIOFEEDBACK; HEART RATE
20  REM  R. HALLGREN, APPLE II, 11-05-81
21  DIM V(300):V(1) = 12:V(2) = 12
22  FOR I = 16384 TO 16459: READ D: POKE I,D: NEXT I
23  POKE 1022,00: POKE 1023,03: POKE 1016,72: POKE 1017,8
24  POKE 1018,88: POKE 1019,40: POKE 1020,104: POKE 1021,96
26  POKE 768,8: POKE 769,238: POKE 770,15: POKE 771,3: POKE 772,40: POKE
     773,165: POKE 774,69: POKE 775,64
27  CALL 1016
29  GOSUB 1000
30  HGR : HCOLOR= 3
32  HPLOT 0,0 TO 0,150: HPLOT  TO 270,150
50  REM  AVERAGE HEART RATE
52  FOR I = 3 TO 270
53 Q = 0: POKE 783,0
56  GOSUB 1100
58 Q = Q + 1
60 X =  PEEK (783): IF X < 30 THEN  GOTO 56
70 V(I) = (V(I - 1) + V(I - 2) + 2 * Q) / 3
80  HPLOT I,(150 - 6 * V(I))
90  NEXT I
200  REM  PLOT AVERAGE
1000  REM  INTRODUCTION
1010  HOME
1020  PRINT "THIS IS A DEMONSTRATION PROGRAM FOR"
1022  PRINT "CONTROLLING HEART RATE USING"
1024  PRINT "BIOFEEDBACK IN CONJUNCTION WITH THE LOW"
1026  PRINT "SPEED A/D CONVERTER AND A DATA PLOT": PRINT "ROUTINE.": PRINT
     "": PRINT ""
1028  PRINT "THE PROGRAM WILL PLOT A POINT": PRINT "10 SECONDS.": PRINT "
     ": PRINT ""
1030  PRINT "PRESS THE SPACE BAR TO CONTINUE."
1032  GET K$: IF K$ <  > " " THEN  GOTO 1032
1099  RETURN
1100  REM  SAMPLE PULSE DETECTOR
1110  CALL 16384
1120  FOR R = 1 TO 50: NEXT R
1199  RETURN
10000  DATA    141,176,73,142,177,73,140,178,73,8,88,141,242,192,173,241,
     192,41,128
10002  DATA  201,128,208,247,173,240,192,141,162,73,41,128,201,128,208,24
     4,173
10004  DATA  162,73,41,4,201,0,208,223,173,240,192,141,162,73,41,32,201,3
     2,208,244
10006  DATA  173,162,73,41,15,201,2,48,202,173,176,73,174,177,73,172,178,
     73,40,96
```

```
4000-   8D B0 49    STA   $49B0
4003-   8E B1 49    STX   $49B1
4006-   8C B2 49    STY   $49B2
4009-   08          PHP
400A-   8D F2 C0    STA   $C0F2
400D-   AD F1 C0    LDA   $C0F1
4010-   29 80       AND   #$80
4012-   C9 80       CMP   #$80
4014-   D0 F7       BNE   $400D
4016-   AD F0 C0    LDA   $C0F0
4019-   8D A2 49    STA   $49A2
401C-   29 80       AND   #$80
401E-   C9 80       CMP   #$80
4020-   D0 F4       BNE   $4016
4022-   AD A2 49    LDA   $49A2
4025-   29 04       AND   #$04
4027-   C9 00       CMP   #$00
4029-   D0 DF       BNE   $400A
402B-   AD F0 C0    LDA   $C0F0
402E-   8D A2 49    STA   $49A2
4031-   29 20       AND   #$20
4033-   C9 20       CMP   #$20
4035-   D0 F4       BNE   $402B
4037-   AD A2 49    LDA   $49A2
403A-   29 0F       AND   #$0F
403C-   C9 02       CMP   #$02
403E-   30 CA       BMI   $400A
4040-   AD B0 49    LDA   $49B0
4043-   AE B1 49    LDX   $49B1
4046-   AC B2 49    LDY   $49B2
4049-   28          PLP
404A-   60          RTS
404B-   00          BRK
404C-   00          BRK
404D-   00          BRK
404E-   00          BRK
404F-   77          ???
4050-   9F          ???
4051-   FF          ???
4052-   80          ???
```

LISTING 6.4 Machine language routine contained within the BASIC program.

Once you have confirmed that the system is working correctly, insert your finger into the pulse detector and we will learn some things about your cardiovascular system. Remember that the detector is motion-sensitive, so you should assume a quiet sitting position with your arm and hand supported on some surface. The first thing you will notice is that your heart rate is a function of respiration. When you inhale your heart rate decreases. Also, if you hold your breath for several seconds, you should expect to see a decrease followed by an increase in heart rate. The graphical display on the CRT will be used as the feedback path to your central nervous system. You can alter your heart rate by practicing progressive relaxation exercises. The idea behind these exercises is to learn how to relax by sensing the difference between tension and relaxation. Start by assuming a comfortable position. Starting

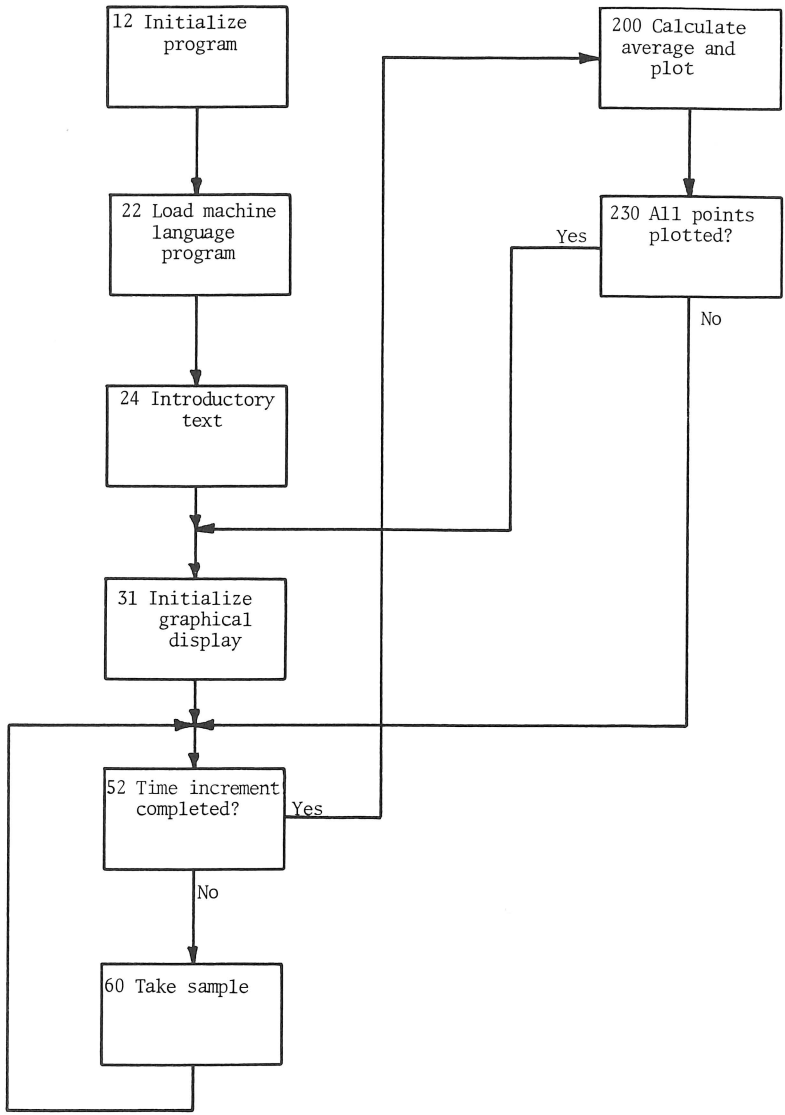
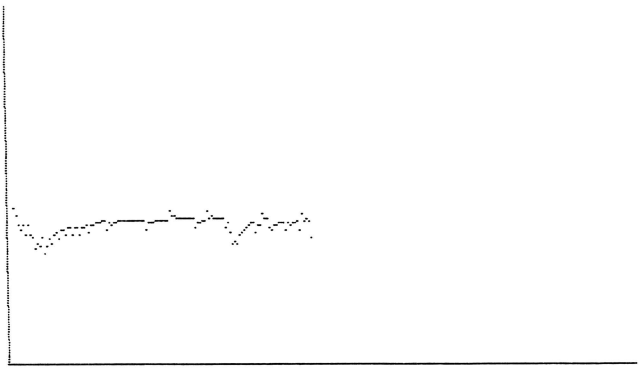


FIGURE 6.8 Flow chart for the BASIC program.

FIGURE 6.9 Graphical display of resting level heart rate.



with the feet, alternately tense and relax your muscles. Suppose you have tensed the muscles in your left leg. When you relax that group of muscles you should feel the leg become limp and heavy. As you progress through this type of relaxation process, your heart rate should decrease, indicating a state of relaxation.

You may want to monitor your heart rate while watching your favorite television program. Sporting events or mystery shows are good candidates for causing your heart rate to significantly increase and decrease. Monitor your pulse rate while you drink a cup of coffee or as you smoke a cigarette. For the more daring individual, you might want to monitor your heart rate as you balance your checkbook at the end of the month.

7

CONTROLLING A VIDEO PLAYBACK DEVICE

The phrase "one picture is worth a thousand words" illustrates the importance of visual representation of material in the learning process. Educators have effectively used snapshots, slides, filmstrips, and motion pictures to aid students while avoiding some of the problems that might occur from direct contact with the subject being studied. While this media serves a purpose, its effectiveness is limited since the viewing speed and the content of the material is fixed, and there is no simple means of allowing individual students to interact with the viewing device.

In an attempt to increase the personal interaction of teaching systems with the student, slide/audio cassette systems have been developed. These systems have been used successfully for many years as a low-cost supplement to textbook instruction at all educational levels. Using individual viewing screens and head-

phones, the student can view and review such things as sequential anatomical dissections, while listening to a detailed description of what they are seeing.

Television has expanded on slide/audio tape systems by allowing the low-cost presentation of prepared lecture material and permitting live demonstrations of such things as surgical procedures to large audiences. The introduction of the videotape recorder has increased the impact of television by allowing lecture and demonstration materials to be recorded and then played back any number of times. Recently, the less expensive videocassette player has made it possible for students to individually view and review prerecorded lecture material. The intimacy of videocassette presentations is surpassed only by the live classroom lecture where the important ingredient of student-teacher interaction is present.

The availability of low-cost personal computing systems has provided another (and more sophisticated) tool for educators. *Computer-assisted instruction* (CAI) is a term used for a system in which the computer carries on a predetermined instructional strategy, and permits conversational interaction with the student. Computers are most recognized for their high-speed computational ability. Because of this, computers can be used in real-time simulation of complex physical systems and, when interfaced with a graphic display, the computer can be very effective in assisting students in their understanding of these systems.

While the use of the small personal computer in an educational environment is not a new concept, the use of a personal computer to interactively control a videocassette player is. Videotaped material is abundant and readily available. Often the student will not need to review a complete lecture, but will only be concerned with a specific segment. In a case such as this, the computer can be used to provide a menu from which the student can choose the desired segment. The computer then is responsible for finding the starting point of the desired segment, initiating the PLAY command, and stopping the presentation when the end of the segment is reached. The interaction of the computer and the video device can also be used as a teaching machine where the computer is used to control the presentation of videotaped lectures. At appropriate times, the lecture could be interrupted and questions asked of the viewer. Depending on the response, the

viewer would be allowed to continue, would be supplied with remedial material, or would just be returned to the start of the most recently viewed segment. This provision of immediate feedback is an important part of the system concept and is a particularly strong feature of computer-assisted instruction. Theoretically, this system should have the following advantages over conventional methods of instruction such as a group lecture:

1. Students can proceed through material at a rate which is consistent with their ability.
2. Correct responses to questions allow additional material to be presented. Incorrect responses cause material to be repeated, or supplementary material to be presented.
3. Material presentation can be organized so that special guidance can be given to correct deficiencies in individual educational backgrounds.
4. Teaching material can be organized for an optimal sequence of presentation.
5. The student is forced to play an active part in the learning process.

The design of the Sony Betamax SL0-320 videocassette recorder makes interfacing the Apple II computer to it a relatively easy task. Table 7.1 shows the control, status, and timing lines that are available from the interface connector on the back of the Betamax. During the recording process, a timing signal is recorded onto the videotape. This timing signal, available on pin 15 of the Auto Search control unit interface connector, can be sampled by the computer and used to index the tape to any relative location. There are two status signals that are available at the interface connector: one signal (CASSETTE IN*) indicates when the video-

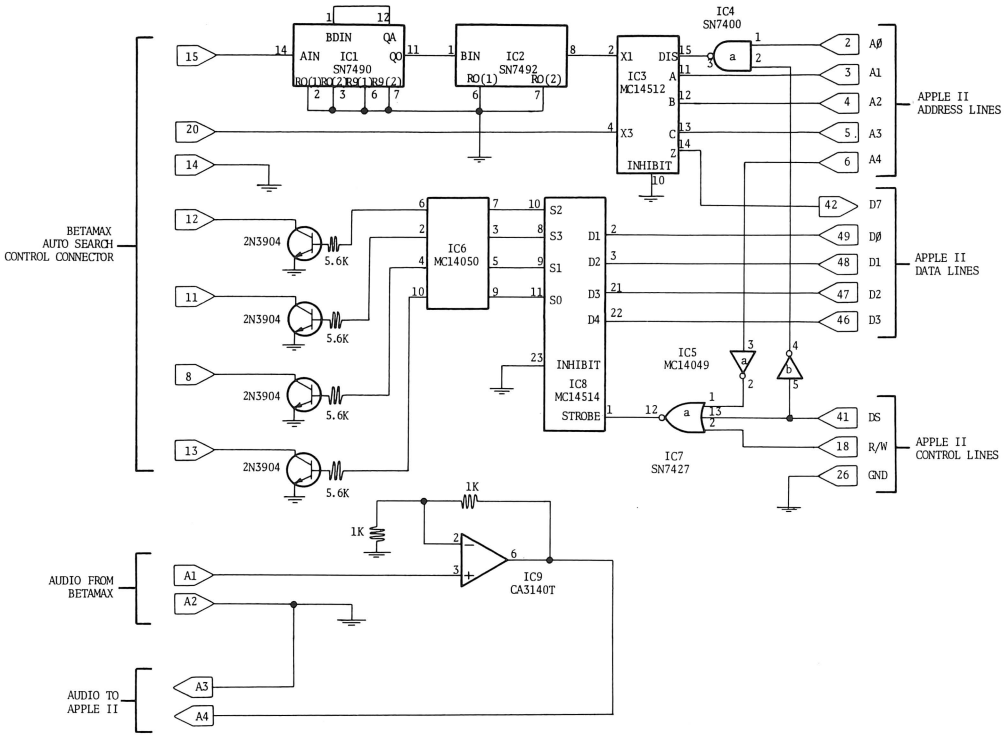
TABLE 7.1 Betamax status and control signals available through the pins that connect the recorder to the RM-300 Auto Search control unit.

Betamax Connector Pin	Signal	Source/ Destination
CN1-20	BEGINNING OF TAPE*	Status signal from Betamax
CN1-7	CASSETTE IN*	Status signal from Betamax
CN1-11	REWIND*	Command signal to Betamax
CN1-8	STOP*	Command signal to Betamax
CN1-13	PLAY*	Command signal to Betamax
CN1-12	FAST FORWARD*	Command signal to Betamax
CN1-15	COUNT*	Timing signal from Betamax

cassette has been inserted into the player and the other signal (BEGINNING OF TAPE*) indicates when the videocassette tape has been fully rewound. These signals were not used in the system that is being described, but certainly could be used if a modification of the system concept makes it desirable. Four control lines (STOP*, PLAY*, FAST FORWARD*, and REWIND*) are also available at the interface connector, and are used to indicate to the Betamax the desired mode of operation.

Figure 7.1 shows the Betamax to Apple II interface in schematic form. The left side of the schematic shows connections

FIGURE 7.1 Betamax/Apple II interface schematic.



Number	Type	+5	-5	GND
IC1	SN7490	5	---	10
IC2	SN7492	5	---	10
IC3	MC14512	16	---	8
IC4	SN7400	14	---	7
IC5	MC14049	1	---	8
IC6	MC14050	1	---	8
IC7	SN7427	14	---	7
IC8	MC14514	24	---	12
IC9	CA3140T	7	4	---

made to the Betamax through the RM-300 Auto Search control unit connector, while the right side of the schematic shows the connections made to the Apple II through the I/O bus connector. Line 15 (COUNT*) from the Betamax carries the timing signal formatted onto the videotape. This signal is divided by a factor of sixty by the combined action of integrated circuits IC1 (SN7490) and IC2 (SN7492). IC3 (MC14512) is an eight-channel data selector which is used to connect the divided timing signal to the Apple II data line seven (D7). Increased channel sampling capability was incorporated so that the two status lines from the Betamax, or other user-defined status lines, could be sampled if so desired. Data line D7 was chosen because its state is easily tested by rotating its contents into the carry bit. Integrated circuit IC7 (MC14514) is a 4-16 line decoder latch which is used to selectively turn on one of the four transistors, thus causing the Betamax to enter either the PLAY, the REWIND, the FAST FORWARD, or the STOP mode. Table 7.2 shows the function that will be accessed for a given BASIC statement or a given machine language command. Provision was made for storing the computer program on a beginning segment of the videotape. To record the program on the videotape you should amplify the output of the computer going to the cassette recorder during a SAVE operation by a factor of ten. Figure 7.2 shows a simple circuit for doing this (refer to Appendix B for a description of the circuit). In order for the audio to be recorded, you will have to provide both the audio signal and a video signal. IC12 (MC14528) is a dual monostable multivibrator configured so that it switches the Betamax into the PLAY mode

TABLE 7.2 Software commands, in both BASIC and 6502 machine language, necessary to activate the Betamax control lines.

Control Signal	BASIC Command	Machine Language Command
REWIND*	POKE-16142,3	LDA #03 STA $C0F2
STOP*	POKE-16142,0	LDA #00 STA $C0F2
PLAY*	POKE-16142,1	LDA #01 STA $C0F2
FAST FORWARD*	POKE-16142,2	LDA #02 STA $C0F2

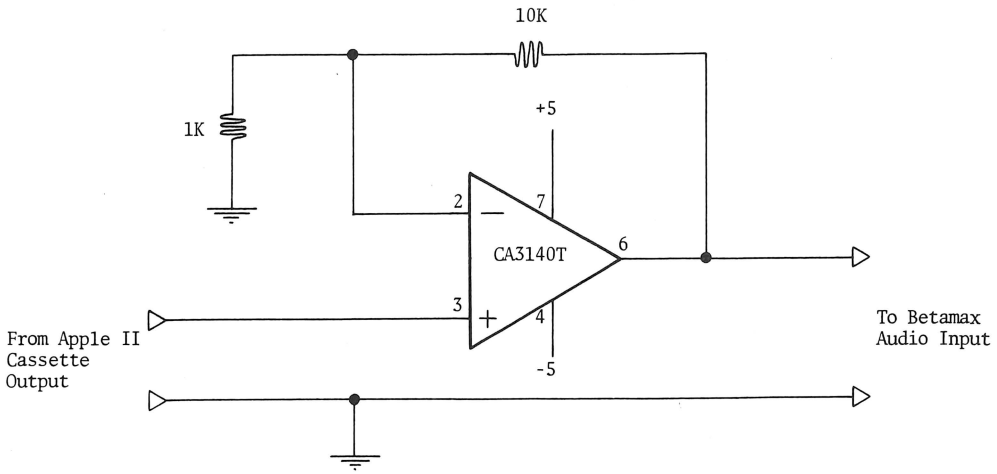


FIGURE 7.2 Operational amplifier circuit for recording Apple II cassette output into the video tape.

when LOAD is entered from the Apple II keyboard, and switches it into the STOP mode when the program has been loaded. IC11 (CA3140T) buffers the audio output from the Betamax to the Apple II cassette audio input during the program load operation.

Once you have completed construction of the interface, you should perform the following tests to make sure that it is working correctly:

1. For each of the Betamax control functions listed in Table 7.2, execute the two BASIC commands associated with the control function. The Betamax should respond in an appropriate manner.
2. Load the Apple II with the test program that is shown in Listing 7.1. Using a prerecorded video tape placed in the cassette player, execute the program. The program should exercise the following player functions:
   FAST FORWARD
   PLAY
   STOP
   REWIND
   STOP
3. If everything functions correctly up to this point, try storing the test program on the beginning segment of a blank videocassette. Remember to connect the audio cables from the Apple II to the Betamax and back again. Remember also to provide some type of video

LISTING 7.1 Betamax/Apple II test program.

```
10  REM  TEST PROGRAM FOR THE BETAMAX/APPLE II INTERFACE
50  REM  START
51  GOSUB 12000: REM  LOAD MACHINE LANGUAGE ROUTINE
52  POKE 771,0: POKE 772,0
53  POKE  - 16142,14: HOME
70 X =  PEEK ( - 16137)
72  IF X < 127 THEN  GOTO 80
74  POKE  - 16142,3
76  GOTO 70
80  POKE  - 16142,14
1000  REM  EXERCISE BETAMAX CONTROL FUNCTIONS
1010 SR = 100:SP = 150
1011  HOME
1012  GOTO 10000
1014  FOR I = 1 TO 2000: NEXT I
1020 SR = 100:SP = 100
10000  REM  CONTROLLER ROUTINE
10002 R1 = 0:R2 = 0:P1 = 0:P2 = 0
10010 X =  PEEK (771) + 256 *  PEEK (772)
10020 R1 = SR
10021 R1 = R1 - 256
10022  IF R1 = 0 THEN  GOTO 10030
10023  IF R1 > 0 THEN  GOTO 10032
10024  IF R1 < 0 THEN  GOTO 10035
10030 R2 = R2 + 1: GOTO 10090
10032 R2 = R2 + 1: GOTO 10021
10035 R1 = R1 + 256
10050 P1 = SP
10051 P1 = P1 - 256
10052  IF P1 = 0 THEN  GOTO 10080
10053  IF P1 > 0 THEN  GOTO 10082
10054  IF P1 < 0 THEN  GOTO 10085
10080 P2 = P2 + 1: GOTO 10090
10082 P2 = P2 + 1: GOTO 10051
10085 P1 = P1 + 256
10090  IF X < SR THEN  GOTO 10100
10092  IF X > SR THEN  GOTO 10200
10094  IF X = SR THEN  GOTO 10300
10100  REM  FAST FORWARD
10110  POKE 773,R1: POKE 774,R2
10112  POKE  - 16142,2: CALL 784
10114  POKE  - 16142,0
10116  GOTO 10300
10200  REM  REWIND
10202 R3 = 0:R4 = 0
10210 R3 = SR + 2
10211 R3 = R3 - 256
10212  IF R3 = 0 THEN  GOTO 10220
10213  IF R3 > 0 THEN  GOTO 10230
10214  IF R3 < 0 THEN  GOTO 10240
10220 R4 = R4 + 1: GOTO 10250
10230 R4 = R4 + 1: GOTO 10211
10240 R3 = R3 + 256
10250  POKE 773,R3: POKE 774,R4
10252  POKE  - 16142,3: CALL 864
10254  POKE  - 16142,0
10256  POKE 771,R1: POKE 772,R2
10300  REM  PLAY
10310  POKE 773,P1: POKE 774,P2
10320  POKE  - 16142,1: CALL 784
10400  REM  STOP
10410  POKE  - 16142,0
10412  POKE  - 16142,14
```

LISTING 7.1 (*Continued*)

```
10420  RETURN
11000  REM  GRAPHIC INTRODUCTION
11012  HOME : GR : COLOR= 2
11020  VLIN 0,11 AT 0: VLIN 0,11 AT 12: PLOT 1,0: PLOT 2,2: PLOT 3,4: PLOT
     4,6: PLOT 5,8: PLOT 6,10: PLOT 7,8: PLOT 8,6: PLOT 9,4: PLOT 10,2: PLOT
     11,0: PLOT 6,11: REM  M
11025  VLIN 0,11 AT 0: VLIN 0,5 AT 15: HLIN 15,25 AT 5: VLIN 6,11 AT 25: HLIN
     25,15 AT 11: HLIN 15,25 AT 0: REM  S
11030  VLIN 0,11 AT 29: VLIN 0,11 AT 39: HLIN 29,39 AT 11: REM  U
11035  VLIN 28,39 AT 0: HLIN 1,10 AT 28: HLIN 0,10 AT 39: REM  C
11040  HLIN 13,23 AT 28: HLIN 13,23 AT 39: VLIN 28,39 AT 13: VLIN 28,39 AT
     23: REM  O
11045  VLIN 28,39 AT 27: VLIN 28,39 AT 39: PLOT 28,28: PLOT 29,30: PLOT 3
     0,32: PLOT 31,34: PLOT 32,36: PLOT 33,38: PLOT 33,39: PLOT 34,36: PLOT
     35,34: PLOT 36,32: PLOT 37,30: PLOT 38,28: REM  M
11090  GET A$
11099  RETURN
12000  REM  MACHINE LANGUAGE ROUTINE
12010  POKE 768,234: POKE 769,234: POKE 770,234: POKE 771,234: POKE 772,2
     34: POKE 773,234: POKE 774,234: POKE 775,234: POKE 776,234: POKE 777
     ,234: POKE 778,234: POKE 779,234
12012  POKE 780,234: POKE 781,234: POKE 782,234: POKE 783,234
12020  POKE 784,008: POKE 785,072: POKE 786,173: POKE 787,243: POKE 788,1
     92: POKE 789,042: POKE 790,176: POKE 791,250
12025  POKE 792,173: POKE 793,243: POKE 794,192: POKE 795,042: POKE 796,1
     44: POKE 797,250: POKE 798,238: POKE 799,003
12030  POKE 800,003: POKE 801,208: POKE 802,003: POKE 803,238: POKE 804,0
     04: POKE 805,003: POKE 806,173: POKE 807,003
12035  POKE 808,003: POKE 809,205: POKE 810,005: POKE 811,003: POKE 812,2
     08: POKE 813,228: POKE 814,173: POKE 815,004
12040  POKE 816,003: POKE 817,205: POKE 818,006: POKE 819,003: POKE 820,2
     08: POKE 821,220: POKE 822,104: POKE 823,040: POKE 824,096
12045  POKE 864,008: POKE 865,072: POKE 866,173: POKE 867,243: POKE 868,1
     92: POKE 869,042: POKE 870,176: POKE 871,250
12050  POKE 872,173: POKE 873,243: POKE 874,192: POKE 875,042: POKE 876,1
     44: POKE 877,250: POKE 878,056: POKE 879,173
12055  POKE 880,003: POKE 881,003: POKE 882,233: POKE 883,001: POKE 884,1
     41: POKE 885,003: POKE 886,003: POKE 887,173
12060  POKE 888,004: POKE 889,003: POKE 890,233: POKE 891,000: POKE 892,1
     41: POKE 893,004: POKE 894,003: POKE 895,173
12065  POKE 896,003: POKE 897,003: POKE 898,205: POKE 899,005: POKE 900,0
     03: POKE 901,208: POKE 902,219: POKE 903,173
12070  POKE 904,004: POKE 905,003: POKE 906,205: POKE 907,006: POKE 908,0
     03: POKE 909,208: POKE 910,211: POKE 911,104
12075  POKE 912,040: POKE 913,096
12999  RETURN
```

signal to the Betamax during the recording process. If you now rewind the tape and enter LOAD, you should see the Betamax begin to play, and the computer should sound a tone, indicating that a normal load is taking place.

The software portion of the controller was written in two parts:

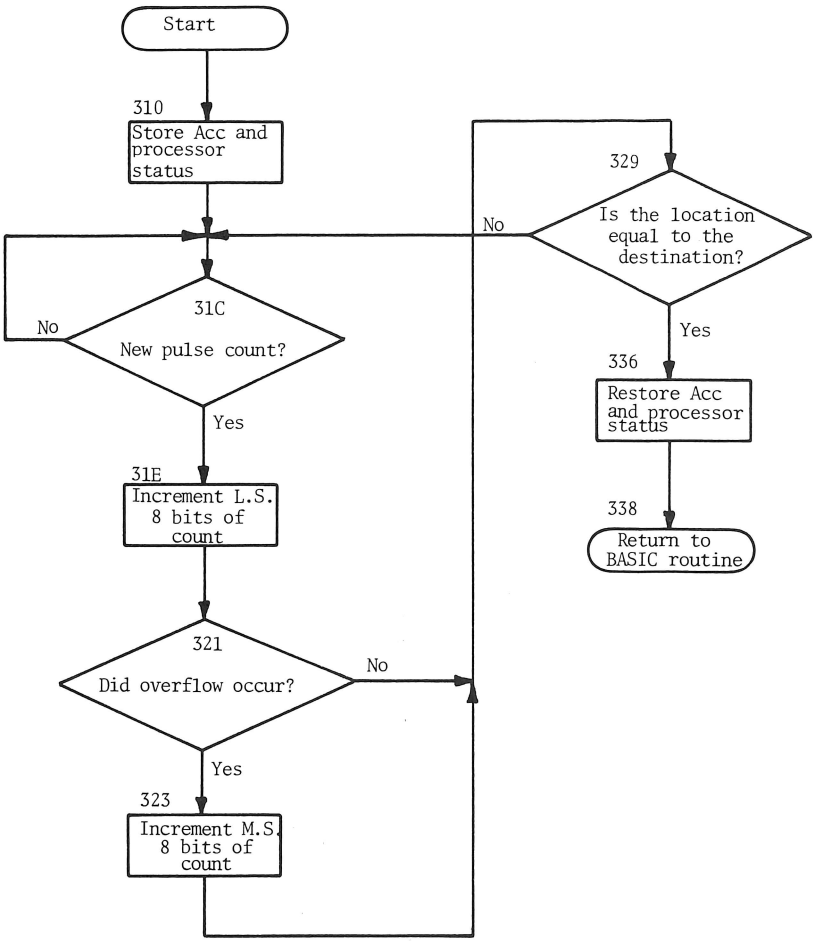
1. Two machine language routines were written to count the pulses coming from the timing track stored on the videotape, and to determine when the desired destination on the videotape had been

reached. One routine is used when the tape is moving forward and the other routine is used when the tape is moving backward.

2. A routine was written in Applesoft BASIC to load the desired tape destination, and to control the operational mode of the cassette player.

Figure 7.3 shows a flow chart of the machine language routine which is used when the tape is moving forward, and Listing 7.2 shows the actual program with comments. Figure 7.4 shows a flow chart of the machine language routine which is used when

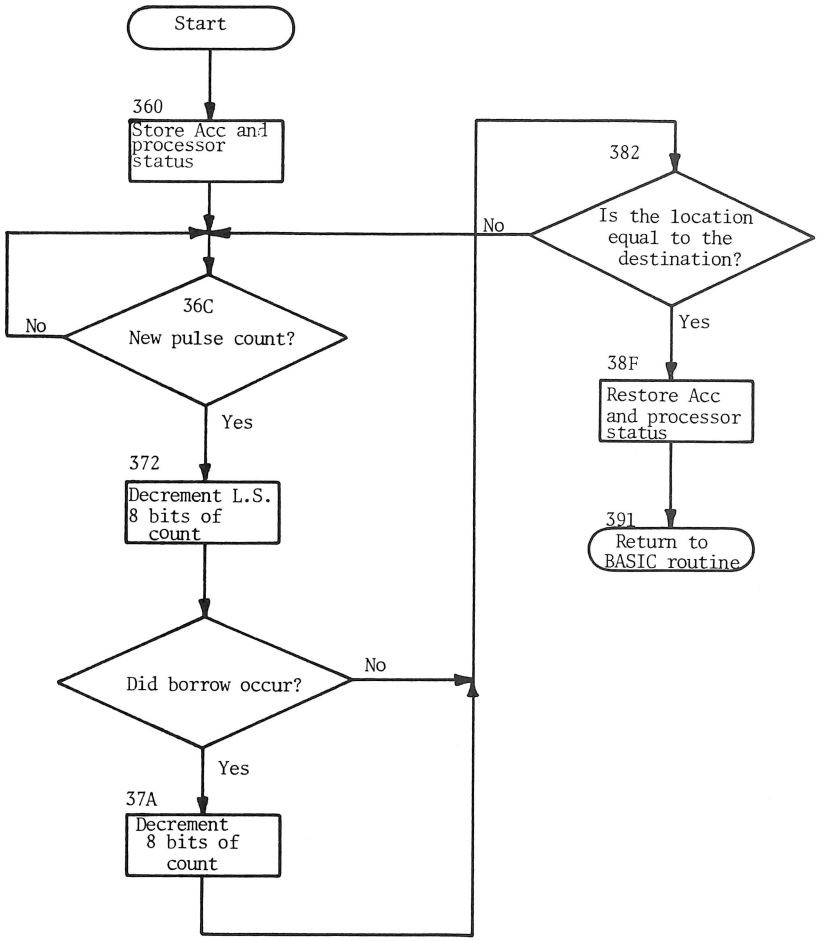
FIGURE 7.3 Flow chart of the machine language routine for incrementing and comparing the videotape location count.



LISTING 7.2 Machine language program for incrementing and comparing the videotape location count.

```
310   08       PHP            Save processor status
311   48       PHA            Save Accumulator
312   ADF3C0   LDA   $C0F3     Save processor status
315   2A       ROL            Rotate bit 7 into carry
316   B0FA     BCS   $312      Branch if carry set
318   ADF3C0   LDA   $C0F3     Sample count line
31B   2A       ROL            Rotate bit 7 into carry
31C   90FA     BCC   $318      Branch if carry clear
31E   EE0303   INC   $303      Increment least sig bit
321   D003     BNE   $326      Branch if no overflow
323   EE0403   INC   $304      Increment most sig 8 bits
326   AD0303   LDA   $303      Load least sig 8 bits
329   CD0503   CMP   $305      Compare with stop count
32C   D0E4     BNE   $312      Branch if not equal
32E   AD0403   LDA   $304      Load most sig 8 bits
331   CD0603   CMP   $306      Compare with stop count
334   D0DC     BNE   $312      Branch if not equal
336   68       PLA            Restore accumulator
337   28       PLP            Restore processor status
338   60       RTS            Return form subroutine
```

FIGURE 7.4 Flow chart of the machine language routine for decrementing and comparing the videotape location count.



the tape is moving backward, and Listing 7.3 shows the actual program with comments. Upon entering either routine, the processor status and the accumulator are pushed onto the stack. The line containing the pulses from the timing track on the video tape is then sampled until it has been determined that the tape has moved a distance equal to one pulse width. A register containing two 8-bit words is then either incremented or decremented depending on whether the tape is being moved forward or in reverse. The contents of this register is then compared to the contents of a register containing the two 8-bit words representing the destination. If the two registers are equal, the tape has reached its destination and the computer returns to the BASIC routine. If the two registers are not equal, the program goes back to wait for the next timing pulse.

Figure 7.5 shows a flow chart of a BASIC routine which has been used for demonstration purposes, and Listing 7.4 shows the actual program with comments. There is an initial decision point at line 232 where a student decides whether he or she needs to watch the whole program or just selected parts. After viewing a segment of instructional material, the student is asked a series of

LISTING 7.3 Machine language program for decrementing and comparing the videotape location count.

```
Hex   Code     Mnemonic       Comments
Adr

360   08       PHP            Save processor status
361   48       PHA            Save accumulator
362   ADF3C0   LDA   $C0F3    Sample count line
365   2A       ROL            Rotate bit 7 into carry
366   B0FA     BCS   $362     Branch if carry set
368   ADF3C0   LDA   $C0F3    Sample count line
36B   2A       ROL            Rotate bit 7 into carry
36C   90FA     BCC   $368     Branch if carry clear
36E   38       SEC            Set carry
36F   AD0303   LDA   $303     Load least sig 8 bits
372   E901     SBC   #$01     Decrement least sig 8 bits
374   8D0303   STA   $303     Save
377   AD0403   LDA   $304     Load most sig 8 bits
37A   E900     SBC   #$00     Decrement if borrow
37C   8D0403   STA   $304     Save
37F   AD0303   LDA   $303     Load least sig 8 bits
382   CD0503   CMP   $305     Compare with stop count
385   D0DB     BNE   $362     Branch if not equal
387   AD0403   LDA   $304     Load most sig 8 bits
38A   CD0603   CMP   $306     Compare with stop count
38D   D0D3     BNE   $362     Branch if not equal
38F   68       PLA            Restore accumulator
390   28       PLP            Restore processor status
391   60       RTS            Return from subroutine
```

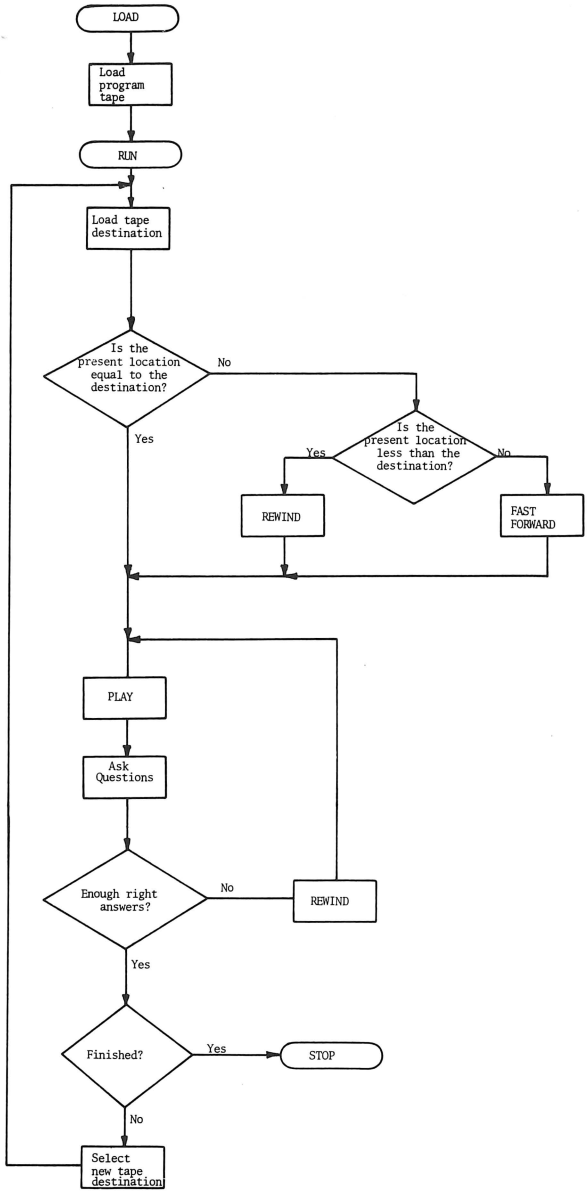


FIGURE 7.5 Flow chart for a demonstration program written in BASIC.

questions designed to test retention and comprehension of the material which has been viewed. If retention and/or comprehension is below a specified level, the videotape is rewound to the segment start point and the material is re-presented to the student. Once comprehension and retention are demonstrated, the student is allowed to continue on to new material.

LISTING 7.4 Betamax/Apple II demonstration routine: Hypercalcemia.

```
50  REM  START
51  GOSUB 12000: REM  LOAD MACHINE LANGUAGE ROUTINE
52  POKE 771,0: POKE 772,0
53  POKE  - 16142,14: HOME
54 X =  PEEK ( - 16133)
56  IF X < 127 THEN  GOTO 70
58  VTAB 10
60  PRINT "!!!!!!!!!!LOAD TAPE!!!!!!!!!!"
62  GOTO 54
70 X =  PEEK ( - 16137)
72  IF X < 127 THEN  GOTO 80
74  POKE  - 16142,3
76  GOTO 70
80  POKE  - 16142,14
100  REM  PROGRAM START
102  TEXT : HOME
106  GOSUB 11000: REM  GRAPHIC INTRODUCTION
200  REM  WHOLE PROGRAM OR PARTS?
201  TEXT : HOME : VTAB 8
204  PRINT "****************************************"
205  PRINT "*                                      *"
206  PRINT "* THE FOLLOWING IS A DEMONSTRATION    *"
208  PRINT "*                                      *"
210  PRINT "* OF THE USE OF A VIDEO TAPE           *"
212  PRINT "*                                      *"
214  PRINT "* RECORDER IN INTERACTIVE COMPUTER     *"
216  PRINT "*                                      *"
218  PRINT "* INSTRUCTION.                         *"
220  PRINT "*                                      *"
222  PRINT "****************************************"
223  CALL  - 198
224  VTAB 24: PRINT "PRESS ANY KEY TO CONTINUE.": GET A$
230  HOME : VTAB 6
232  PRINT "****************************************"
234  PRINT "*                                      *"
236  PRINT "* YOU HAVE THE CHOICE OF LOOKING       *"
238  PRINT "*                                      *"
240  PRINT "* AT THE WHOLE VIDEO TAPE OR AT        *"
242  PRINT "*                                      *"
244  PRINT "* SELECTED PARTS.                      *"
246  PRINT "*                                      *"
248  PRINT "* WOULD YOU LIKE TO VIEW THE WHOLE     *"
250  PRINT "*                                      *"
252  PRINT "* TAPE?                                *"
256  PRINT "*                                      *"
258  PRINT "****************************************"
260  VTAB 24: PRINT "PRESS Y FOR YES OR N FOR NO.": CALL  - 198: GET A$
261  IF A$ = "*" THEN  GOTO 50
262  IF A$ = "Y" THEN  GOTO 1000
264  IF A$ = "N" THEN  GOSUB 2000
265  GOTO 230
266  VTAB 24: PRINT "PRESS Y FOR YES OR N FOR NO!": CALL  - 198: GET A$: GOTO
     262
867 ,3: POKE 868,233: POKE 869,1
1000  REM  WHOLE TAPE PRESENTATION
1002  HOME
1010 SR = 0:SP = 85
1012  GOSUB 10000
1014  GOSUB 2200
1020 SR = 92:SP = 114
1022  GOSUB 10000
1024  GOSUB 3100
1030 SR = 122:SP = 172
1032  GOSUB 10000
```

LISTING 7.4 (*Continued*)

```
1034  GOSUB 4100
1040 SR = 179:SP = 236
1042  GOSUB 10000
1044  GOSUB 5100
1050 SR = 241:SP = 308
1052  GOSUB 10000
1054  GOSUB 6100
1060 SR = 314:SP = 440
1062  GOSUB 10000
1064  GOSUB 7100
1070 SR = 446:SP = 822
1072  GOSUB 10000
1074  GOSUB 8100
1080 SR = 829:SP = 1100
1082  GOSUB 10000
1084  GOSUB 9100
1090  GOTO 230
1999  END
2000  REM  SELECTED TAPE PRESENTATION
2002  HOME
2010  PRINT "*************************************"
2012  PRINT "*                                   *"
2014  PRINT "* CHOSE FROM THE FOLLOWING TOPICS   *"
2020  PRINT "*                                   *"
2022  PRINT "*  1. CALCIUM REGULATION            *"
2024  PRINT "*                                   *"
2026  PRINT "*  2. HYPERCALCEMIA SYMPTOMS        *"
2028  PRINT "*                                   *"
2030  PRINT "*  3. CAUSES FOR HYPERCALCEMIA      *"
2032  PRINT "*                                   *"
2034  PRINT "*  4. TESTING FOR HYPERCALCENIA     *"
2036  PRINT "*                                   *"
2038  PRINT "*  5. RANGE OF NORMAL CALCIUM LEVELS*"
2040  PRINT "*                                   *"
2042  PRINT "*  6. CORRECTION FACTORS            *"
2046  PRINT "*                                   *"
2048  PRINT "*  7. CASE HISTORY---MILD CASE      *"
2049  PRINT "*                                   *"
2050  PRINT "*  8. CASE HISTORY---SEVERE CASE    *"
2051  PRINT "*                                   *"
2052  PRINT "*************************************"
2054  VTAB 22: CALL  - 198
2056  PRINT "PRESS THE KEY CORRESPONDING TO YOUR     CHOICE.": GET A$
2060  HOME
2070  IF A$ = "1" THEN  GOSUB 2100: GOTO 2000
2072  IF A$ = "2" THEN  GOSUB 3000: GOTO 2000
2074  IF A$ = "3" THEN  GOSUB 4000: GOTO 2000
2076  IF A$ = "4" THEN  GOSUB 5000: GOTO 2000
2078  IF A$ = "5" THEN  GOSUB 6000: GOTO 2000
2080  IF A$ = "6" THEN  GOSUB 7000: GOTO 2000
2082  IF A$ = "7" THEN  GOSUB 8000: GOTO 2000
2084  IF A$ = "8" THEN  GOSUB 9000: GOTO 2000
2085  IF A$ = "*" THEN  GOTO 50
2086  CALL  - 198: VTAB 22
2088  PRINT "PRESS THE KEY CORRESPONDING TO YOUR     CHOICE.": GET A$: GOTO
    2070
2100 SR = 0:SP = 85
2110 SR = 0:SP = 85
2112  GOSUB 10000
2200  REM  FIRST QUESTION
2201 R = 0: HOME
2202  PRINT "*************************************"
2204  PRINT "*                                   *"
2206  PRINT "* HYPERCALCEMIA IS BEING DIAGNOSED  *"
```

```
2208  PRINT "*                                    *"
2210  PRINT "* MORE BECAUSE OF:                   *"
2212  PRINT "*                                    *"
2214  PRINT "*  1. THE INCREASE IN STRESS IN OUR *"
2216  PRINT "*     DAILY LIVES                    *"
2218  PRINT "*                                    *"
2220  PRINT "*  2. THE ABILITY OF CLINICAL        *"
2222  PRINT "*     LABORATORIES TO ROUTINELY TEST*"
2224  PRINT "*     CALCIUM LEVELS                 *"
2226  PRINT "*                                    *"
2228  PRINT "*  3. THE INCREASE IN SUGAR IN OUR   *"
2230  PRINT "*     DIET                           *"
2232  PRINT "*                                    *"
2234  PRINT "**************************************"
2236  VTAB 20: CALL  - 198
2237  POKE  - 16368,0
2238  PRINT "PRESS THE KEY CORRESPONDING TO  YOUR     CHOICE.": GET A$
2240  IF A$ = "2" THEN  GOTO 2250
2242  IF A$ = "*" THEN  GOTO 50
2244  PRINT "INCORRECT"
2246  GOTO 2255
2250  PRINT "CORRECT"
2254 R = R + 1
2255  FOR I = 0 TO 1000: NEXT I
2300  REM  SECOND QUESTION
2302  HOME
2303  PRINT "**************************************"
2304  PRINT "*                                    *"
2305  PRINT "* WHAT THREE HORMONES ARE PRIMARILY *"
2306  PRINT "*                                    *"
2307  PRINT "* RESPONSIBLE FOR CONTROLLING THE   *"
2308  PRINT "*                                    *"
2310  PRINT "* MOVEMENT OF CALCIUM BETWEEN THE   *"
2311  PRINT "*                                    *"
2312  PRINT "* EXTRACELLAR FLUID AND BONE,KIDNEY *"
2313  PRINT "*                                    *"
2314  PRINT "* AND GASTROINTESTINAL TRACT?        *"
2316  PRINT "*                                    *"
2317  PRINT "**************************************"
2330  VTAB 17
2331  POKE  - 16368,0
2332  CALL  - 198: INPUT "1.";A1$
2334  GOSUB 2900
2335  VTAB 19: POKE  - 16368,0
2336  CALL  - 198: INPUT "2.";A2$
2337  GOSUB 2920
2338  VTAB 21: POKE  - 16368,0
2340  CALL  - 198: INPUT "3.";A3$
2341  GOSUB 2930
2342  FOR I = 0 TO 1000: NEXT I
2346  IF R < 2 THEN  GOTO 2382
2350  HOME
2351  PRINT "YOU HAVE SCORED WELL ENOUGH TO"
2352  CALL  - 922
2353  PRINT "PROCEED ON TO NEW MATERIAL."
2354  FOR I = 0 TO 1000: NEXT I
2355  RETURN
2382  HOME
2384  PRINT "YOU HAVE NOT SCORED WELL ENOUGH"
2385  CALL  - 922
2386  PRINT "TO CONTINUE ON TO NEW MATERIAL!"
2387  CALL  - 922
2388  PRINT "PAY CLOSE ATTENTION TO THE LECTURE"
2389  CALL  - 922
2390  PRINT "MATERIAL!"
```

LISTING 7.4 (*Continued*)

```
2392  FOR I = 0 TO 1000
2393  NEXT I
2394  GOTO 2100
2900 B1$ = "D":B2$ = "VITAMIN D":B3$ = "PTH":B4$ = "PARATHYROID":B5$ = "P
     ARATHYROID HORMONE":B6$ = "CALCITONIN"
2905  IF A1$ = "*" THEN  GOTO 50
2910  IF A1$ = B1$ THEN  GOTO 2960
2911  IF A1$ = B2$ THEN  GOTO 2960
2912  IF A1$ = B3$ THEN  GOTO 2960
2913  IF A1$ = B4$ THEN  GOTO 2960
2914  IF A1$ = B5$ THEN  GOTO 2960
2915  IF A1$ = B6$ THEN  GOTO 2960
2916  GOTO 2950
2920  IF A2$ = B1$ THEN  GOTO 2960
2921  IF A2$ = B2$ THEN  GOTO 2960
2922  IF A2$ = B3$ THEN  GOTO 2960
2923  IF A2$ = B4$ THEN  GOTO 2960
2924  IF A2$ = B5$ THEN  GOTO 2960
2925  IF A2$ = B6$ THEN  GOTO 2960
2926  IF A2$ = "*" THEN  GOTO 50
2927  GOTO 2950
2930  IF A3$ = B1$ THEN  GOTO 2960
2931  IF A3$ = B2$ THEN  GOTO 2960
2932  IF A3$ = B3$ THEN  GOTO 2960
2933  IF A3$ = B4$ THEN  GOTO 2960
2934  IF A3$ = B5$ THEN  GOTO 2960
2935  IF A3$ = B6$ THEN  GOTO 2960
2936  IF A3$ = "*" THEN  GOTO 50
2950 CV =  PEEK (37): VTAB CV
2952  HTAB 20: PRINT "INCORRECT"
2954  RETURN
2960 CV =  PEEK (37): VTAB CV
2962  HTAB 20: PRINT "CORRECT"
2963 R = R + 1
2964  RETURN
2999  RETURN
3000  REM  HYPERCALCEMIA SYMPTOMS
3010 SR = 92:SP = 114
3012  GOSUB 10000
3100  REM  FIRST QUESTION
3102 R = 0: HOME
3104  VTAB 8
3105  PRINT "**************************************"
3106  PRINT "*                                    *"
3108  PRINT "* PATIENTS HAVING MILD               *"
3110  PRINT "*                                    *"
3112  PRINT "* HYPERCALCEMIA CAN BE DESCRIBED     *"
3114  PRINT "*                                    *"
3116  PRINT "* AS BEING":CV =  PEEK (37)
3118  VTAB CV: HTAB 37: PRINT "*"
3120  PRINT "*                                    *"
3122  PRINT "**************************************"
3123  POKE  - 16368,0
3124  VTAB CV: HTAB 12: INPUT A$
3130  VTAB CV: HTAB 37: PRINT "*"
3132  IF A$ = "ASYMPTOMATIC" THEN  GOTO 3150
3134  IF A$ = "*" THEN  GOTO 50
3140  VTAB 22: PRINT "INCORRECT"
3142  GOTO 3154
3150  VTAB 22: PRINT "CORRECT"
3152 R = R + 1
3154  FOR I = 0 TO 1000: NEXT I
3200  REM  SECOND QUESTION
3202  HOME
```

```
3210  PRINT "************************************"
3212  PRINT "*                                  *"
3214  PRINT "* LIST TWO SYMPTOMS OF HYPER-      *"
3216  PRINT "*                                  *"
3218  PRINT "* CALCEMIA WHICH ARE ASSOCIATED    *"
3219  PRINT "*                                  *"
3220  PRINT "* WITH DEHYDRATION AND IMPAIRED    *"
3222  PRINT "*                                  *"
3224  PRINT "* RENAL FUNCTION.                  *"
3226  PRINT "*                                  *"
3228  PRINT "************************************"
3230  VTAB 17
3231  POKE  - 16368,0
3232  CALL  - 198: INPUT "1.";A1$
3233  GOSUB 3300
3234  POKE  - 16368,0: CALL  - 198: INPUT "2.";A2$
3235  GOSUB 3320
3236  FOR I = 0 TO 1000: NEXT I
3237  IF R < 2 THEN  GOTO 3252
3240  HOME
3242  PRINT "YOU HAVE SCORED WELL ENOUGH TO"
3243  CALL  - 922
3244  PRINT "CONTINUE ON TO NEW MATERIAL."
3245  FOR I = 0 TO 1000: NEXT I
3246  RETURN
3252  HOME
3254  PRINT "YOU HAVE NOT SCORED WELL ENOUGH"
3256  CALL  - 922
3258  PRINT "TO CONTINUE ON TO NEW MATERIAL!"
3260  CALL  - 922
3262  PRINT "PAY CLOSE ATTENTION TO THE LECTURE"
3264  CALL  - 922
3266  PRINT "MATERIAL!"
3268  FOR I = 0 TO 1000: NEXT I
3270  GOTO 3000
3300 B1$ = "VOMITING":B2$ = "POLYURIA"
3310  IF A1$ = B1$ THEN  GOTO 3360
3312  IF A1$ = B2$ THEN  GOTO 3360
3313  IF A1$ = "*" THEN  GOTO 50
3314  GOTO 3350
3320  IF A2$ = B1$ THEN  GOTO 3360
3322  IF A2$ = B2$ THEN  GOTO 3360
3324  IF A2$ = "*" THEN  GOTO 50
3350 CV =  PEEK (37): VTAB CV
3352  HTAB 20: PRINT "INCORRECT"
3354  RETURN
3360 CV =  PEEK (37): VTAB CV
3362  HTAB 20: PRINT "CORRECT"
3364 R = R + 1
3366  RETURN
4000  REM  CAUSES FOR HYPERCALCEMIA
4010 SR = 122:SP = 172
4012  GOSUB 10000
4100  REM  FIRST QUESTION
4102 R = 0: HOME
4108  VTAB 6
4110  PRINT "************************************"
4112  PRINT "*                                  *"
4114  PRINT "* THE MOST IMPORTANT PATHOGENETIC  *"
4116  PRINT "*                                  *"
4118  PRINT "* MECHANISM OF HYPERCALCEMIA IS:   *"
4120  PRINT "*                                  *"
4122  PRINT "*                                  *"
4124  PRINT "*  1. INCREASED BONE ABSORPTION    *"
4126  PRINT "*                                  *"
4128  PRINT "*  2. INCREASED BONE RESORPTION    *"
```

LISTING 7.4 (*Continued*)

```
4130  PRINT "*                                    *"
4132  PRINT "*  3. DECREASED BONE ABSORPTION      *"
4134  PRINT "*                                    *"
4136  PRINT "**************************************"
4138  VTAB 22
4140  CALL  - 198
4142  PRINT "PRESS THE KEY CORRESPONDING TO YOUR     CHOICE.": GET A$
4143  POKE  - 16368,0
4144  IF A$ = "2" THEN  GOTO 4150
4145  IF A$ = "*" THEN  GOTO 50
4146  PRINT "INCORRECT"
4148  GOTO 4155
4150  PRINT "CORRECT"
4152 R = R + 1
4155  FOR I = 0 TO 1000: NEXT I
4200  REM  SECOND QUESTION
4202  HOME
4208  VTAB 6
4210  PRINT "**************************************"
4212  PRINT "*                                    *"
4214  PRINT "* INCREASED BONE RESORPTION RESULTS *"
4216  PRINT "*                                    *"
4218  PRINT "* FROM THREE CAUSES, LIST TWO        *"
4220  PRINT "*                                    *"
4222  PRINT "* OF THEM.                          *"
4224  PRINT "*                                    *"
4226  PRINT "**************************************"
4228  VTAB 17
4229  POKE  - 16368,0
4230  CALL  - 198: INPUT "1.";A1$
4231  GOSUB 4280: VTAB 19
4232  POKE  - 16368,0: CALL  - 198: INPUT "2.";A2$
4233  GOSUB 4285
4234  FOR I = 0 TO 1000: NEXT I
4236  GOTO 4300
4280 B1$ = "HYPERTHYROIDISM":B2$ = "METASTATIC CANCER":B3$ = "BONE-RESORB
    ING HORMONE"
4281  IF A1$ = B1$ THEN  GOTO 4295
4282  IF A1$ = B2$ THEN  GOTO 4295
4283  IF A1$ = B3$ THEN  GOTO 4295
4284  IF A1$ = "*" THEN  GOTO 50
4285  GOTO 4290
4286  IF A2$ = B1$ THEN  GOTO 4295
4287  IF A2$ = B2$ THEN  GOTO 4295
4288  IF A2$ = B3$ THEN  GOTO 4295
4289  IF A2$ = "*" THEN  GOTO 50
4290 CV =  PEEK (37): VTAB CV: HTAB 30
4291  PRINT "INCORRECT"
4292  RETURN
4295 CV =  PEEK (37): VTAB CV: HTAB 30
4296  PRINT "CORRECT"
4297 R = R + 1
4298  RETURN
4300  REM  THIRD QUESTION
4302  HOME
4308  VTAB 6
4310  PRINT "**************************************"
4312  PRINT "*                                    *"
4314  PRINT "* INCREASED GASTROINTESTINAL        *"
4316  PRINT "*                                    *"
4318  PRINT "* ABSORPTION OF CALCIUM IS DUE TO:  *"
4320  PRINT "*                                    *"
4322  PRINT "*                                    *"
4324  PRINT "*  1. VITAMIN D INTOXICATION         *"
```

```
4326  PRINT "*                                    *"
4328  PRINT "*  2. THYROTOXICOSIS                 *"
4330  PRINT "*                                    *"
4332  PRINT "*  3. PAGET'S DISEASE                *"
4334  PRINT "*                                    *"
4336  PRINT "*************************************"
4338  CALL  - 198: VTAB 22
4339  POKE  - 16368,0
4340  PRINT "PRESS THE KEY CORRESPONDING TO YOUR     CHOICE.": GET A$
4341  IF A$ = "1" THEN  GOTO 4348
4342  IF A$ = "*" THEN  GOTO 50
4343  PRINT "INCORRECT": GOTO 4350
4348  PRINT "CORRECT"
4349 R = R + 1
4350  FOR I = 0 TO 1000: NEXT I
4351  IF R > 2 THEN  GOTO 4400
4352  HOME
4354  PRINT "YOU HAVE NOT SCORED WELL ENOUGH"
4356  CALL  - 922
4358  PRINT "TO CONTINUE ON TO NEW MATERIAL."
4360  CALL  - 922
4362  PRINT "PAY CLOSE ATTENTION TO THE LECTURE"
4364  CALL  - 922
4366  PRINT "MATERIAL."
4368  FOR I = 0 TO 1000: NEXT I
4370  GOTO 4000
4400  HOME
4402  PRINT "YOU HAVE SCORED WELL ENOUGH TO"
4403  CALL  - 922
4404  PRINT "CONTINUE ON TO NEW MATERIAL."
4406  FOR I = 0 TO 1000: NEXT I
4408  RETURN
5000  REM  TESTING FOR HYPERCALCEMIA
5010 SR = 179:SP = 236
5012  GOSUB 10000
5100  REM  FIRST QUESTION
5102 R = 0: HOME
5108  VTAB 6
5110  PRINT "*************************************"
5112  PRINT "*                                   *"
5114  PRINT "* WHAT ARE THREE METHODS CURRENTLY  *"
5116  PRINT "*                                   *"
5118  PRINT "* USED TO MEASURE THE TOTAL SERUM   *"
5120  PRINT "*                                   *"
5122  PRINT "* CALCIUM CONCENTRATION?            *"
5124  PRINT "*                                   *"
5126  PRINT "*************************************"
5128  CALL  - 922
5130  POKE  - 16368,0
5132  CALL  - 198: INPUT "1.";A1$
5134  GOSUB 5900
5136  POKE  - 16368,0
5138  CALL  - 198: INPUT "2.";A2$
5140  GOSUB 5920
5142  POKE  - 16368,0
5144  CALL  - 198: INPUT "3.";A3$
5146  GOSUB 5930
5148  FOR I = 0 TO 1000: NEXT I
5150  IF R < 2 THEN  GOTO 5191
5152  HOME
5154  PRINT "YOU HAVE SCORED WELL ENOUGH TO"
5156  CALL  - 922
5158  PRINT "CONTINUE ON TO NEW MATERIAL."
5160  FOR I = 0 TO 1000: NEXT I
5162  RETURN
5191  HOME
```

LISTING 7.4 (*Continued*)

```
5192  PRINT "YOU HAVE NOT SCORED WELL ENOUGH": CALL  - 922
5193  PRINT "TO CONTINUE ON TO NEW MATERIAL.": CALL  - 922
5194  PRINT "PAY CLOSE ATTENTION TO THE LECTURE": CALL  - 922
5196  PRINT "MATERIAL."
5197  FOR I = 0 TO 1000: NEXT I
5198  GOTO 5000
5900 B1$ = "ATOMIC ABSORPTION":B2$ = "ATOMIC ABSORPTION SPECTROPHOTOMETER
     ":B3$ = "SPECTROPHOTOMETER"
5902 B4$ = "COLORIMETER":B5$ = "COLORIMETRIC METHODS":B6$ = "AUTOMATIC TI
     TRATION":B7$ = "TITRATION"
5906  IF A1$ = "*" THEN  GOTO 50
5908  IF A1$ = B1$ THEN  GOTO 5960
5910  IF A1$ = B2$ THEN  GOTO 5960
5912  IF A1$ = B3$ THEN  GOTO 5960
5914  IF A1$ = B4$ THEN  GOTO 5960
5916  IF A1$ = B5$ THEN  GOTO 5960
5917  IF A1$ = B6$ THEN  GOTO 5960
5918  IF A1$ = B7$ THEN  GOTO 5960
5919  GOTO 5950
5920  IF A2$ = B1$ THEN  GOTO 5960
5922  IF A2$ = B2$ THEN  GOTO 5960
5923  IF A2$ = B3$ THEN  GOTO 5960
5924  IF A2$ = B4$ THEN  GOTO 5960
5925  IF A2$ = B5$ THEN  GOTO 5960
5926  IF A2$ = B6$ THEN  GOTO 5960
5927  IF A2$ = B7$ THEN  GOTO 5960
5928  IF A2$ = "*" THEN  GOTO 50
5929  GOTO 5950
5930  IF A3$ = B1$ THEN  GOTO 5960
5932  IF A3$ = B2$ THEN  GOTO 5960
5933  IF A3$ = B6$ THEN  GOTO 5960
5934  IF A3$ = B3$ THEN  GOTO 5960
5935  IF A3$ = B7$ THEN  GOTO 5960
5936  IF A3$ = B4$ THEN  GOTO 5960
5937  IF A3$ = B5$ THEN  GOTO 5960
5950 CV =  PEEK (37): VTAB CV: HTAB 30
5952  PRINT "INCORRECT"
5955  RETURN
5960 CV =  PEEK (37): VTAB CV: HTAB 30
5962  PRINT "CORRECT"
5964 R = R + 1
5966  RETURN
6000  REM  RANGE OF NORMAL CALCIUM LEVELS
6010 SR = 241:SP = 308
6012  GOSUB 10000
6100  REM  FIRST QUESTION
6102 R = 0: HOME
6108  VTAB 6
6110  PRINT "*************************************"
6112  PRINT "*                                   "
6114  PRINT "*    THE NORMAL SERUM CALCIUM       *"
6116  PRINT "*                                   *"
6118  PRINT "*    CONCENTRATION RANGES FROM:     *"
6120  PRINT "*                                   *"
6122  PRINT "*                                   *"
6124  PRINT "*  1.  88-104 MG/100ML              *"
6126  PRINT "*                                   *"
6128  PRINT "*  2.  8.8-10.4 MG/100ML            *"
6130  PRINT "*                                   *"
6132  PRINT "*  3. .88-1.04 MG/100ML             *"
6134  PRINT "*                                   *"
6136  PRINT "*************************************"
6138  VTAB 22: CALL  - 198
6139  POKE  - 16368,0
```

```
6140  PRINT "PRESS THE KEY CORRESPONDING TO YOUR     CHOICE.": GET A$
6141  IF A$ = "2" THEN  GOTO 6145
6142  IF A$ = "*" THEN  GOTO 50
6143  PRINT "INCORRECT"
6144  GOTO 6147
6145  PRINT "CORRECT"
6146 R = R + 1
6147  FOR I = 0 TO 1000: NEXT I
6148  IF R = 1 THEN  GOTO 6170
6150  CALL  - 922
6151  HOME : PRINT "YOU HAVE NOT SCORED WELL ENOUGH": CALL  - 922
6152  PRINT "TO CONTINUE ONTO NEW MATERIAL.": CALL  - 922
6154  PRINT "PAY CLOSE ATTENTION TO THE LECTURE": CALL  - 922
6155  PRINT "MATERIAL."
6158  FOR I = 0 TO 1000: NEXT I
6160  GOTO 6000
6170  HOME
6172  PRINT "YOU HAVE SCORED WELL ENOUGH TO": CALL  - 922
6174  PRINT "CONTINUE ON TO NEW MATERIAL."
6175  FOR I = 0 TO 1000: NEXT I
6176  RETURN
7000  REM  CORRECTION FACTORS
7010 SR = 314:SP = 440
7012  GOSUB 10000
7100  REM  FIRST QUESTION
7102 R = 0: HOME
7110  PRINT "*************************************"
7112  PRINT "*                                   *"
7114  PRINT "* GIVEN THE FOLLOWING RESULTS FORM  *"
7116  PRINT "*                                   *"
7118  PRINT "* THE LABORATORY ANALYSIS, WHAT     *"
7120  PRINT "*                                   *"
7122  PRINT "* WOULD THE CORRECTED CALCIUM       *"
7124  PRINT "*                                   *"
7126  PRINT "* CONCENTRATION BE EQUAL TO?        *"
7127  PRINT "*                                   *"
7128  PRINT "*      CALCIUM----10.2 MG/100ML     *"
7129  PRINT "*      ALBUMIN-----3.5 MG/100ML     *"
7130  PRINT "*      NORMAL ALBUMIN--4.5 MG/100ML *"
7134  PRINT "*                                   *"
7136  PRINT "*  1.  11 MG/100ML                  *"
7138  PRINT "*                                   *"
7140  PRINT "*  2.  9.6 MG/100ML                 *"
7142  PRINT "*                                   *"
7144  PRINT "*  3.  13.8 MG/100ML                *"
7146  PRINT "*                                   *"
7148  PRINT "*************************************"
7150  VTAB 22: CALL  - 198
7151  POKE  - 16368,0
7152  PRINT "PRESS THE KEY CORRESPONDING TO YOUR     CHOICE.": GET A$
7153  IF A$ = "*" THEN  GOTO 50
7154  IF A$ = "1" THEN  GOTO 7160
7156  PRINT "INCORRECT"
7158  GOTO 7165
7160  PRINT "CORRECT"
7162 R = R + 1
7165  FOR I = 0 TO 1000: NEXT I
7200  REM  SECOND QUESTION
7202  HOME
7210  PRINT "*************************************"
7212  PRINT "*                                   *"
7213  PRINT "* GIVEN THE FOLLOWING RESULTS FROM  *"
7214  PRINT "*                                   *"
7218  PRINT "* THE LABORATORY ANALYSIS, WHAT     *"
7220  PRINT "*                                   *"
```

LISTING 7.4 (*Continued*)

```
7223  PRINT "* WOULD THE CORRECTED CALCIUM       *"
7224  PRINT "*                                   *"
7225  PRINT "* CONCENTRATION BE EQUAL TO?        *"
7226  PRINT "*                                   *"
7230  PRINT "*         CALCIUM----10.2 MG/100ML  *"
7232  PRINT "*         ALBUMIN-----5.5 MG/100ML  *"
7234  PRINT "*         NORMAL ALBUMIN-4.5 MG/100ML*"
7236  PRINT "*                                   *"
7238  PRINT "*                                   *"
7240  PRINT "*  1.  11 MG/100ML                  *"
7241  PRINT "*                                   *"
7242  PRINT "*  2.  9.6 MG/100ML                 *"
7244  PRINT "*                                   *"
7245  PRINT "*  3.  13.8 MG/100ML                *"
7250  PRINT "*                                   *"
7252  PRINT "*************************************"
7254  VTAB 22: CALL  - 198
7255  POKE  - 16368,0
7256  PRINT "PRESS THE KEY CORRESPONDING TO YOUR     CHOICE.": GET A$
7257  IF A$ = "*" THEN  GOTO 50
7258  IF A$ = "2" THEN  GOTO 7290
7259  PRINT "INCORRECT": GOTO 7295
7262  HOME
7264  PRINT "YOU HAVE NOT SCORED WELL ENOUGH": CALL  - 922
7266  PRINT "TO CONTINUE ON TO NEW MATERIAL.": CALL  - 922
7270  PRINT "PAY CLOSE ATTENTION TO THE LECTURE": CALL  - 922
7272  PRINT "MATERIAL."
7274  FOR I = 0 TO 1000: NEXT I
7276  GOTO 7000
7280  HOME
7281  PRINT "YOU HAVE SCORED WELL ENOUGH TO": CALL  - 922
7282  PRINT "CONTINUE ON TO NEW MATERIAL."
7284  FOR I = 0 TO 1000: NEXT I
7286  RETURN
7290  PRINT "CORRECT"
7292 R = R + 1
7295  FOR I = 0 TO 1000: NEXT I
7296  IF R = 2 THEN  GOTO 7280
7297  GOTO 7262
8000  REM  CASE HISTORY(MILD)
8010 SR = 446:SP = 822
8012  GOSUB 10000
8100  REM  FIRST QUESTION
8102  RETURN
9000  REM  CASE HISTORY(SEVERE)
9010 SR = 831:SP = 1100
9012  GOSUB 10000
9100  REM  FIRST QUESTION
9102  RETURN
10000  REM  CONTROLLER ROUTINE
10002 R1 = 0:R2 = 0:P1 = 0:P2 = 0
10010 X =  PEEK (771) + 256 *  PEEK (772)
10020 R1 = SR
10021 R1 = R1 - 256
10022  IF R1 = 0 THEN  GOTO 10030
10023  IF R1 > 0 THEN  GOTO 10032
10024  IF R1 < 0 THEN  GOTO 10035
10030 R2 = R2 + 1: GOTO 10090
10032 R2 = R2 + 1: GOTO 10021
10035 R1 = R1 + 256
10050 P1 = SP
10051 P1 = P1 - 256
10052  IF P1 = 0 THEN  GOTO 10080
10053  IF P1 > 0 THEN  GOTO 10082
```

```
10054  IF P1 < 0 THEN  GOTO 10085
10080 P2 = P2 + 1: GOTO 10090
10082 P2 = P2 + 1: GOTO 10051
10085 P1 = P1 + 256
10090  IF X < SR THEN  GOTO 10100
10092  IF X > SR THEN  GOTO 10200
10094  IF X = SR THEN  GOTO 10300
10100  REM  FAST FORWARD
10110  POKE 773,R1: POKE 774,R2
10112  POKE  - 16142,2: CALL 784
10114  POKE  - 16142,0
10116  GOTO 10300
10200  REM  REWIND
10202 R3 = 0:R4 = 0
10210 R3 = SR + 2
10211 R3 = R3 - 256
10212  IF R3 = 0 THEN  GOTO 10220
10213  IF R3 > 0 THEN  GOTO 10230
10214  IF R3 < 0 THEN  GOTO 10240
10220 R4 = R4 + 1: GOTO 10250
10230 R4 = R4 + 1: GOTO 10211
10240 R3 = R3 + 256
10250  POKE 773,R3: POKE 774,R4
10252  POKE  - 16142,3: CALL 864
10254  POKE  - 16142,0
10256  POKE 771,R1: POKE 772,R2
10300  REM  PLAY
10310  POKE 773,P1: POKE 774,P2
10320  POKE  - 16142,1: CALL 784
10400  REM  STOP
10410  POKE  - 16142,0
10412  POKE  - 16142,14
10420  RETURN
11000  REM  GRAPHIC INTRODUCTION
11012  HOME : GR : COLOR= 2
11020  VLIN 0,11 AT 0: VLIN 0,11 AT 12: PLOT 1,0: PLOT 2,2: PLOT 3,4: PLOT
     4,6: PLOT 5,8: PLOT 6,10: PLOT 7,8: PLOT 8,6: PLOT 9,4: PLOT 10,2: PLOT
     11,0: PLOT 6,11: REM  M
11025  VLIN 0,11 AT 0: VLIN 0,5 AT 15: HLIN 15,25 AT 5: VLIN 6,11 AT 25: HLIN
     25,15 AT 11: HLIN 15,25 AT 0: REM  S
11030  VLIN 0,11 AT 29: VLIN 0,11 AT 39: HLIN 29,39 AT 11: REM  U
11035  VLIN 28,39 AT 0: HLIN 1,10 AT 28: HLIN 0,10 AT 39: REM  C
11040  HLIN 13,23 AT 28: HLIN 13,23 AT 39: VLIN 28,39 AT 13: VLIN 28,39 AT
     23: REM  O
11045  VLIN 28,39 AT 27: VLIN 28,39 AT 39: PLOT 28,28: PLOT 29,30: PLOT 3
     0,32: PLOT 31,34: PLOT 32,36: PLOT 33,38: PLOT 33,39: PLOT 34,36: PLOT
     35,34: PLOT 36,32: PLOT 37,30: PLOT 38,28: REM  M
11090  GET A$
11099  RETURN
12000  REM  MACHINE LANGUAGE ROUTINE
12010  POKE 768,234: POKE 769,234: POKE 770,234: POKE 771,234: POKE 772,2
     34: POKE 773,234: POKE 774,234: POKE 775,234: POKE 776,234: POKE 777
     ,234: POKE 778,234: POKE 779,234
12012  POKE 780,234: POKE 781,234: POKE 782,234: POKE 783,234
12020  POKE 784,008: POKE 785,072: POKE 786,173: POKE 787,243: POKE 788,1
     92: POKE 789,042: POKE 790,176: POKE 791,250
12025  POKE 792,173: POKE 793,243: POKE 794,192: POKE 795,042: POKE 796,1
     44: POKE 797,250: POKE 798,238: POKE 799,003
12030  POKE 800,003: POKE 801,208: POKE 802,003: POKE 803,238: POKE 804,0
     04: POKE 805,003: POKE 806,173: POKE 807,003
12035  POKE 808,003: POKE 809,205: POKE 810,005: POKE 811,003: POKE 812,2
     08: POKE 813,228: POKE 814,173: POKE 815,004
12040  POKE 816,003: POKE 817,205: POKE 818,006: POKE 819,003: POKE 820,2
     08: POKE 821,220: POKE 822,104: POKE 823,040: POKE 824,096
12045  POKE 864,008: POKE 865,072: POKE 866,173: POKE 867,243: POKE 868,1
     92: POKE 869,042: POKE 870,176: POKE 871,250
```

LISTING 7.4 (*Continued*)

```
12050  POKE 872,173: POKE 873,243: POKE 874,192: POKE 875,042: POKE 876,1
     44: POKE 877,250: POKE 878,056: POKE 879,173
12055  POKE 880,003: POKE 881,003: POKE 882,233: POKE 883,001: POKE 884,1
     41: POKE 885,003: POKE 886,003: POKE 887,173
12060  POKE 888,004: POKE 889,003: POKE 890,233: POKE 891,000: POKE 892,1
     41: POKE 893,004: POKE 894,003: POKE 895,173
12065  POKE 896,003: POKE 897,003: POKE 898,205: POKE 899,005: POKE 900,0
     03: POKE 901,208: POKE 902,219: POKE 903,173
12070  POKE 904,004: POKE 905,003: POKE 906,205: POKE 907,006: POKE 908,0
     03: POKE 909,208: POKE 910,211: POKE 911,104
12075  POKE 912,040: POKE 913,096
12999  RETURN
```

8

DATA ANALYSIS TECHNIQUES

CURVE FITTING

The observation of naturally-occurring phenomena is often the basic approach of a scientific researcher. Data are recorded as a function of some dependent variable (a parameter that is not a function of the phenomena that is being observed) and the researcher then draws conclusions based on the relationship between the two variables. The first step that usually occurs after the data have been gathered is the posing of question: What mathematical formula best describes the relationship between the two variables?

Linear Regression

The simplest relationship that two variables could have is a linear relationship, that is, the dependent variable and the independent variable would increase or decrease with a one-to-one relationship. When a linear relationship occurs, the dependent variable can be expressed as a function of the independent variable by the following equation:

$$y = A\,x + B \qquad \text{where A and B are constants} \tag{8.1}$$

The following program will find values for A and B which will give the closest agreement between the experimental data and Equation 8.1. The technique that will be used is called *linear regression by the method of least squares.*

Listing 8.1 shows the program with comments. The program expects to receive *x* and *y* pairs of data. When all the values have been entered, the program computes the coefficient for Equation 8.1 and calculates a coefficient of determination to give a relative indication of the goodness of fit. Once the equation has been generated, you may predict values of *y* for given values of *x*.

EXAMPLE A forgetful electrical engineering professor wakes up one morning and thinks that he might have a fever. A search through his medicine cabinet produces an oral thermometer, but it slips through his fingers and falls to the floor, breaking into a thousand pieces. Disgusted with himself, he suddenly realizes that he has an outdoor thermometer which is calibrated in degrees Fahrenheit, but it is much to big to fit in his mouth. He remembers that the skin-temperature biofeedback project he built has a thermistor probe, but that it is not calibrated. He suspects that the probe is linear and that the relationship between the output voltage from the interface and temperature might be equal to Equation 8.2. He knows that if he could get a few data points he could run the linear regression program and solve for the coefficients of the equation:

$$T = aV + b \tag{8.2}$$

LISTING 8.1 BASIC linear regression routine.

```
100  REM  LINEAR REGRESSION
102  REM  R. HALLGREN 3-5-81
110  HOME
130  PRINT "*****************************"
132  PRINT "*                           *"
134  PRINT "* YOU WILL INPUT THE PAIRED  *"
138  PRINT "* VALUES OF DATA THAT YOU    *"
142  PRINT "* HAVE GATHERED.             *"
144  PRINT "*                           *"
146  PRINT "* WHEN ALL DATA PAIRS HAVE   *"
150  PRINT "* BEEN ENTERED, PRESS * TO   *"
154  PRINT "* CALCULATE THE REGRESSION   *"
158  PRINT "* COEFFECIENTS.              *"
159  PRINT "*                           *"
160  PRINT "* PRESS THE SPACE BAR        *"
162  PRINT "* TO CONTINUE.               *"
164  PRINT "*****************************"
180  GET K$
182  IF K$ <  > " " GOTO 180
200  REM  INPUT DATA PAIRS
210 J = 0:K = 0:M = 0:R2 = 0
212 N = 1
230  HOME
240  PRINT "DATA PAIR #";N
242  INPUT "X VALUE ";X(N)
244  INPUT "Y VALUE ";Y(N)
246 N = N + 1
250  PRINT "": PRINT "": PRINT ""
252  PRINT "PRESS * TO CALCULATE"
254  PRINT "COEFFICIENTS."
255  PRINT
256  PRINT "PRESS THE SPACE BAR TO ENTER"
258  PRINT "MORE DATA PAIRS."
260  GET K$
262  IF K$ = "*" GOTO 300
264  IF K$ <  > " " GOTO 260
268  GOTO 230
300  REM  CALCALATE REGRESSION COEFFICIENTS
302 N = N - 1
310  FOR I = 0 TO N
312 J = J + X(I)
314 K = K + Y(I)
316 L = L + (X(I)) ^ 2
318 M = M + (Y(I)) ^ 2
320 R2 = R2 + X(I) * Y(I)
330  NEXT I
340 A = (N * R2 - K * J) / (N * L - J ^ 2)
342 B = (K - A * J) / N
350  HOME
354  PRINT "Y=";A;"* X +";B
400  REM  COMPUTE COEFFICIENT OF DETERMINATION
410 J = A * (R2 = J * K / N)
412 M = M - K ^ 2 / N
414 K = M - J
416 R2 = J / M
420  PRINT
424  PRINT "COEFFICIENT OF DETERMINATION = ";R2
430  PRINT
432  PRINT "DO YOU NEED TO PREDICT VALUES"
434  PRINT "OF Y FOR GIVEN VALUES OF X?"
440  PRINT
442  PRINT "PRESS Y OR N"
444  GET K$
446  IF K$ = "N" THEN  END
448  IF K$ <  > "Y" THEN 444
450  REM  CALCULATE Y FROM VALUES OF X
452  HOME
456  INPUT "X=";X
458  PRINT "Y=";A * X + B
460  GOTO 430
```

He places both the thermometer and the thermistor probe into a sink of warm water and records the following data points:

V(volts)	1.055	1.044	1.014	.984	.974	.943
T(F)	104	103	100	97	96	93

Find the values for a and b? What is the coefficient of determination? If the professor's temperature is equal to 1.006 volts, should he be worried?

Exponential Regression

Another common relationship between data pairs is described by an exponential curve. When such a relationship exists, the dependent variable can be expressed as a function of the independent variable by an equation having the following form:

$$y = A\, e^{Bx} \tag{8.3}$$

The following program will find values for A and B which will give the closest agreement between the experimental data and Equation 8.2. The technique that will be used is called *exponential regression by the method of least squares.*

Listing 8.2 shows the program with comments. The program expects to receive x and y pairs of data. When all the values have been entered, the program computes the coefficients for Equation 8.2 and calculates a coefficient of determination to give a relative indication of the goodness of fit. Once the equation has been determined, you may predict values of y for given values of x.

EXAMPLE Realizing a bargain when he saw one, Fred bought several large capacitors at the local flea market for a very low price. Unfortunately, these capacitors were unmarked. Fred knows that a capacitor, being charged through a series resistor from a fixed voltage source, will exponentially increase in voltage as time increases. By knowing the value of the series resistor, and measuring the voltage across the resistor as a function of time, he should be able to use the exponential regression program to determine the value of the capacitance. Using his high school electronics text, Fred determines that the voltage across the series resistor will be equal to the following equation:

LISTING 8.2 BASIC exponential routine.

```
100  REM  EXPONENTIAL REGRESSION
102  REM  R. HALLGREN 3-5-81
110  HOME
130  PRINT "*******************************"
132  PRINT "*                             *"
134  PRINT "* YOU WILL INPUT THE PAIRED  *"
138  PRINT "* VALUES OF DATA THAT YOU    *"
142  PRINT "* HAVE GATHERED.             *"
144  PRINT "*                             *"
146  PRINT "* WHEN ALL DATA PAIRS HAVE   *"
150  PRINT "* BEEN ENTERED, PRESS * TO   *"
154  PRINT "* CALCULATE THE REGRESSION   *"
158  PRINT "* COEFFECIENTS.              *"
159  PRINT "*                             *"
160  PRINT "* PRESS THE SPACE BAR        *"
162  PRINT "* TO CONTINUE.               *"
164  PRINT "*******************************"
180  GET K$
182  IF K$ <  > " " GOTO 180
200  REM  INPUT DATA PAIRS
210 J = 0:K = 0:M = 0:R2 = 0
212 N = 1
230  HOME
240  PRINT "DATA PAIR #";N
242  INPUT "X VALUE ";X(N)
244  INPUT "Y VALUE ";Y(N)
246 N = N + 1
250  PRINT
252  PRINT "PRESS * TO CALCULATE"
254  PRINT "COEFFICIENTS."
255  PRINT
256  PRINT "PRESS THE SPACE BAR TO ENTER"
258  PRINT "MORE DATA PAIRS."
260  GET K$
262  IF K$ = "*" GOTO 300
264  IF K$ <  > " " GOTO 260
268  GOTO 230
300  REM  CALCALATE REGRESSION COEFFICIENTS
302 N = N - 1
310  FOR I = 1 TO N
311 Y(I) =  LOG (Y(I))
312 J = J + X(I)
314 K = K + Y(I)
316 L = L + (X(I)) ^ 2
318 M = M + (Y(I)) ^ 2
320 R2 = R2 + X(I) * Y(I)
330  NEXT I
340 B = (N * R2 - K * J) / (N * L - J ^ 2)
342 A = (K - B * J) / N
350  HOME
354  PRINT "B=";B
356  PRINT "A="; EXP (A)
400  REM  COMPUTE COEFFICIENT OF DETERMINATION
410 J = B * (R2 - J * K / N)
412 M = M - K ^ 2 / N
414 K = M - J
416 R2 = J / M
420  PRINT
424  PRINT "COEFFICIENT OF DETERMINATION = ";R2
430  PRINT
432  PRINT "DO YOU NEED TO PREDICT VALUES"
434  PRINT "OF Y FOR GIVEN VALUES OF X?"
440  PRINT
442  PRINT "PRESS Y OR N"
444  GET K$
```

LISTING 8.2 (*Continued*)

```
446  IF K$ = "N" THEN  END
448  IF K$ <  > "Y" THEN 444
450  REM  CALCULATE Y FROM VALUES OF X
452  HOME
456  INPUT "T=";X
458  PRINT "V="; EXP (A) *  EXP (B * X)
460  GOTO 430
```

$$
\begin{aligned}
V &= Ee^{-t/RC} \\
\text{where } V &= \text{resistor voltage (volts)} \\
E &= \text{battery voltage (volts)} = 5 \\
R &= \text{resistance (ohms)} = 1000 \\
C &= \text{capacitance (farads)} \\
t &= \text{time (seconds)}
\end{aligned}
\tag{8.4}
$$

Getting out the high speed A/D converter that he built in Chapter 3, Fred gets ready to prove to himself that the capacitors really were a bargain. Fred sets the sampling rate at one sample per second and obtains the following set of data points:

t	0	1	2	3	4	5
V	5	1.9	.7	.25	.109	.042

Find the values for a and b in Equation 8.4 and calculate the capacitance of Fred's capacitor. If he needs ten farads for his plasma discharge generator, will he be able to use this particular capacitor?

Fast Fourier Analysis

The sounds that your ears receive are comprised of many individual frequencies which are summed together to form a complex waveform which gives the sound its characteristic quality. It is possible to take an arbitrary continuous signal, expressed in the time domain, and break it up into a series of individual frequencies. The magnitude of this spectrum at different frequencies is a measure of the frequency content that comprises the original signal. The concept of spectrum finds many practical applications in many varied disciplines including waveform analysis of music, frequency content of muscle voltages, vibrational characteristics of mechanical systems, and so on. Figure 8.1 shows a plot, in the

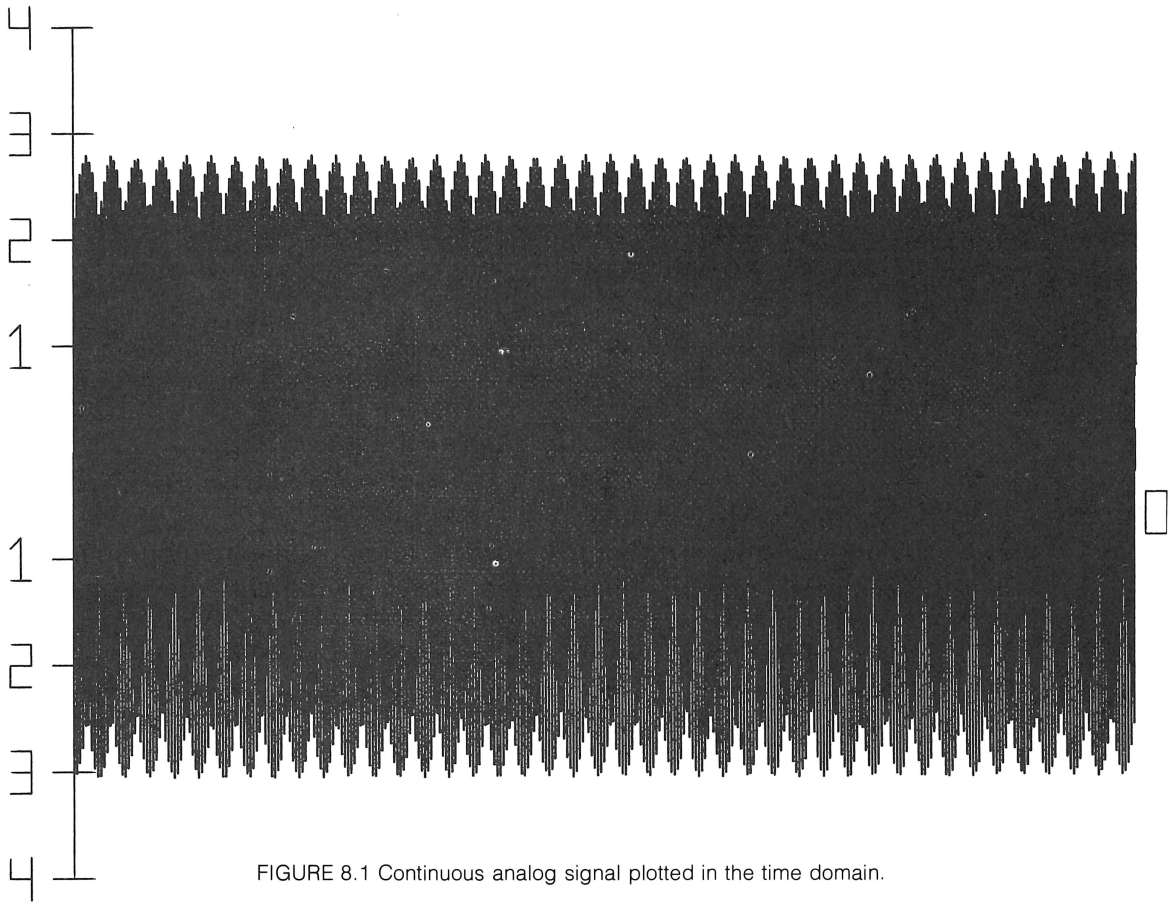


FIGURE 8.1 Continuous analog signal plotted in the time domain.

time domain, of a complex analog waveform. It would be very difficult to come to any conclusions regarding the spectral content of the signal by just visually analyzing it. Figure 8.2 shows the same waveform transformed into the frequency domain by a fast Fourier transform (FFT). You can easily observe a small d.c. component at the far left of the plot and make the statement that the complex waveform contains a single high-frequency signal. In fact, Figure 8.1 is just the plot of a 200 Hz sine wave.

Listing 8.3 shows a program written in Applesoft which performs the fast Fourier routine. The program first gets the data file that we created with the high speed A/D converter that we described in Chapter 3. The FFT routine then mathematically separates the complex waveform into the sum of a number of

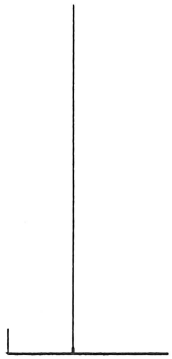


FIGURE 8.2 Signal from Figure 8.1 analyzed by the fast Fourier transform and plotted as a function of frequency.

LISTING 8.3 Fast Fourier routine written in BASIC.

```
10  REM  FFT ROUTINE
12  REM  R. HALLGREN, 11-2-81
14  REM  APPLE II
20  HOME : VTAB 5
34  PRINT "****************************************"
36  PRINT "*                                      *"
38  PRINT "* HOW MANY POINTS DO YOU WANT         *"
40  PRINT "* TO PROCESS?                         *"
42  PRINT "*                                      *"
44  PRINT "*     1. 512                           *"
46  PRINT "*     2. 256                           *"
48  PRINT "*     3. 128                           *"
50  PRINT "*                                      *"
52  PRINT "* PRESS THE NUMBER CORRESPONDING       *"
54  PRINT "* TO THE CHOICE.                       *"
56  PRINT "*                                      *"
58  PRINT "****************************************"
60  INPUT K$
62  IF K$ = "1" THEN L = 9:N = 512: GOTO 80
64  IF K$ = "2" THEN L = 8:N = 256: GOTO 80
66  IF K$ = "3" THEN L = 7:N = 128: GOTO 80
68  GOTO 60
80  GOTO 200
200  REM  DATA FORMATTER SUBROUTINE
201 T = 0
202  DIM X1(N): DIM X2(N):P = 3.14159:X = 24830
203 D$ = "": PRINT D$;"BLOAD DATA($1100),A$6100"
204  HOME : VTAB 10
206  PRINT "DATA IS BEING FORMATTED"
220  FOR Z = 0 TO N - 1
222 X = X + 2
224 V1 =  PEEK (X):V2 =  PEEK (X + 1)
230  IF V1 > 1 THEN  GOTO 300
250 X1(Z) =  - (511 - (V1 * 256 + V2)) / 100
270  NEXT Z
280  GOTO 640
300 X1(Z) = ((V1 - 2) * 256 + V2) / 100
320  GOTO 270
640  REM  SCALE INPUT TIME FUNCTION
642  FOR Z = 0 TO N - 1
650 X1(Z) = X1(Z) / N
660  NEXT Z
670  REM  FFT IN-PLACE ALGORITHM
675  HOME : VTAB 10
```

```
676  PRINT "       FFT CALCULATION IN PROCESS"
680 I1 = N / 2:I2 = 1:V = 2 * P / N
690  FOR I = 1 TO L
700 I3 = 0:I4 = I1
710  FOR K = 1 TO I2
720 X =  INT (I3 / I1)
730  GOSUB 1300
740 I5 = Y
750 Z1 =  COS (V * I5)
760 Z2 =  - SIN (V * I5)
770  FOR M = I3 TO I4 - 1
780 A1 = X1(M):A2 = X2(M)
790 B1 = Z1 * X1(M + I1) - Z2 * X2(M + I1)
800 B2 = Z2 * X1(M + I1) + Z1 * X2(M + I1)
810 X1(M) = A1 + B1:X2(M) = A2 + B2
820 X1(M + I1) = A1 - B1:X2(M + I1) = A2 - B2
830  NEXT M
840 I3 = I3 + 2 * I1:I4 = I4 + 2 * I1
850  NEXT K
860 I1 = I1 / 2:I2 = 2 * I2
870  NEXT I
880  REM  OUTPUT RESULTS
960  HOME : VTAB 10: PRINT "PLOT ON DIGITAL?": INPUT K$
962  IF K$ = "N" THEN  GOTO 970
963  IF K$ <  > "Y" THEN  GOTO 962
966  FOR I = 0 TO 160: READ K: POKE ( - 32800 + I),K: NEXT I
970 B = 0
975  HOME : VTAB 10: PRINT "    CALCULATION IN PROGRESS"
980  FOR Z = 0 TO N / 2
985 X = Z
990  GOSUB 1390
1000  IF X3 > B THEN B = X3
1005 C = 0
1010  NEXT Z
1012  IF K$ = "N" THEN  GOTO 1020
1015  HOME : VTAB 10: PRINT "LOAD PEN AND PRESS ANY KEY": GET A$
1020  HGR2 : HCOLOR= 3
1021  FOR Z = 0 TO N / 2
1022  IF Z > 900 THEN  GOTO 1110
1025 X = Z
1030  GOSUB 1390
1040 X4 =  INT (56 * X3 / B)
1050 K =  INT (10 * X4)
1051  IF K > 600 THEN K = 600
1052  IF K$ = "N" THEN  GOTO 1093
1055  CALL  - 32646: FOR I = 0 TO 10: NEXT I
1056  FOR J = 1 TO K: CALL  - 32712: NEXT J
1057  CALL  - 32653
1058  FOR J = 1 TO K: CALL  - 32681: NEXT J
1092  CALL  - 32695
1093  GOTO 1500
1100  NEXT Z
1105  FOR I = 0 TO N:X2(I) = 0: NEXT I
1110  END
1290  REM  SCRAMBLER SUBROUTINE
1300 Y = 0:N1 = N
1310  FOR W = 1 TO L
1320 N1 = N1 / 2
1330  IF X < N1 THEN  GOTO 1360
1340 Y = Y + 2 ^ (W - 1)
1350 X = X - N1
1360  NEXT W
1370  RETURN
1380  REM  MAGNITUDE(X3) SUBROUTINE
1390  GOSUB 1300
1400 X3 =  SQR (X1(Y) ^ 2 + X2(Y) ^ 2)
```

LISTING 8.3 (*Continued*)

```
1410  RETURN
1500  REM  VIDEO PLOT
1502  FOR R = 0 TO (K / 4)
1504  HPLOT T,(155 - R)
1506  NEXT R
1508 T = T + 1
1599  GOTO 1100
10000  DATA  160,9,24,72,176,7,169,0,141,209,192,144,5,169,1,141,209,192,169,3
10002  DATA  72,169,4,74,144,253,104,233,1,208,245,104,106,136,208,223,160,2,169
10004  DATA  1,141,209,192,169,3,72,169,4,74,144,253,104,233,1,208,245,136,208
10006  DATA  235,96,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
10008  DATA  72,8,169,112,32,224,127,40,104,96,72,8,169,113,76,60,128,72,8,169,114
10010  DATA   76,60,128,72,8,169,115,76,60,128,72,8,169,116,76,60,128,72,8,169,117
10012  DATA  76,60,128,72,8,169,118,76,60,128,72,8,169,119,76,60,128,72,8,169,121
10014  DATA  76,60,128,72,8,169,122,76,60,128
```

discrete frequencies, and plots the magnitude of each frequency component. The frequency spacing between each component is a function of the digitization frequency and the number of points that you have in the routine process. You then have to decide how many of those points you wish to process with the FFT. Using a larger number of points results in greater resolution but requires more processing time. For example, 512 points requires 16 minutes, 256 points requires 8 minutes, and 128 points requires 4 minutes. You can calculate the frequency spacing between each component with Equation 8.5.

$$F = 1/(t*N) \text{ Hz}$$

where F = the distance between each component
t = the time increment between samples
N = the number of processed points (8.5)

If we were sampling an input signal at a rate of 1000 Hz, then t would be equal to .001 seconds. If we then decided to process 512 points, we would expect the distance between components to be equal to 1.95 Hz. This means that if we had digitized a 19.5 Hz sine wave, we would expect to see a peak in the magnitude of the output at the 11th point (the magnitude of the d.c. component occupying the first point).

You can do several things to enhance the utility of these routines:

1. Write programs to plot both the complex waveform and the Fourier transform with the digital plotter developed in Chapter 5.

2. Convert the BASIC program shown in Listing 8.3 into a machine language routine to greatly decrease the time spent processing the data.

To help assure yourself that you have entered the program correctly, I have included a simple program which generates a perfect 100 Hz sine wave and stores it in memory. After loading the main program, key in the following BASIC statements.

```
80 REM
90 Y=24830:T=0
91 FOR Z=0 TO N-1
92 Y=Y+2:X=1+SIN(2*3.14159*100*T)
94 T=T+7.8125E-4
95 POKE Y, 3:POKE (Y+1),100*X
96 NEXT Z
203 REM
```

If everything is working correctly, you should observe a peak in magnitude at the eleventh output.

The following four figures show the results of taking the FFT of 512 points of data from audio data digitized at a rate of 1000 samples per second. Figure 8.3 shows the spectrum of a violin solo. Notice how there are very distinct harmonics displayed. Figure 8.4 shows the spectrum of the speaking voice of a male radio announcer. Notice how the spectrum is rich in low frequency content. Figure 8.5 shows the spectrum of the singing voice of a popular singer who was holding a high clear note when the data was collected.

FIGURE 8.3 Fourier transform of violin solo.

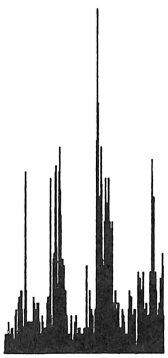


FIGURE 8.4 Fourier transform of the voice of a male radio announcer.

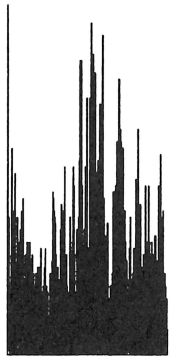
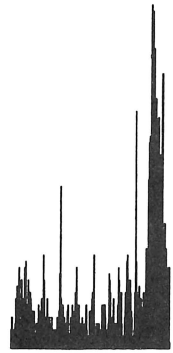


FIGURE 8.5 Fourier transform of the voice of a female singer.



APPENDIX A: CONSTRUCTION TECHNIQUES

Before you start to build, you should have some feeling for the construction options that are available to you. This will allow you to use appropriate construction techniques for specific circuits that you will be building. I am not going into a lot of detail concerning the actual construction process involved in each option, since this has been covered in detail in other publications. However, based on my personal experience, I will summarize the advantages and disadvantages of each process.

If you need to build ten or more boards having the same circuit configuration, you might want to have a custom circuit board constructed. There are usually a number of small companies in any large metropolitan area which can perform this service. Costs will run about $500 for the circuit board layout and about $20 apiece for each circuit board. The cost is directly pro-

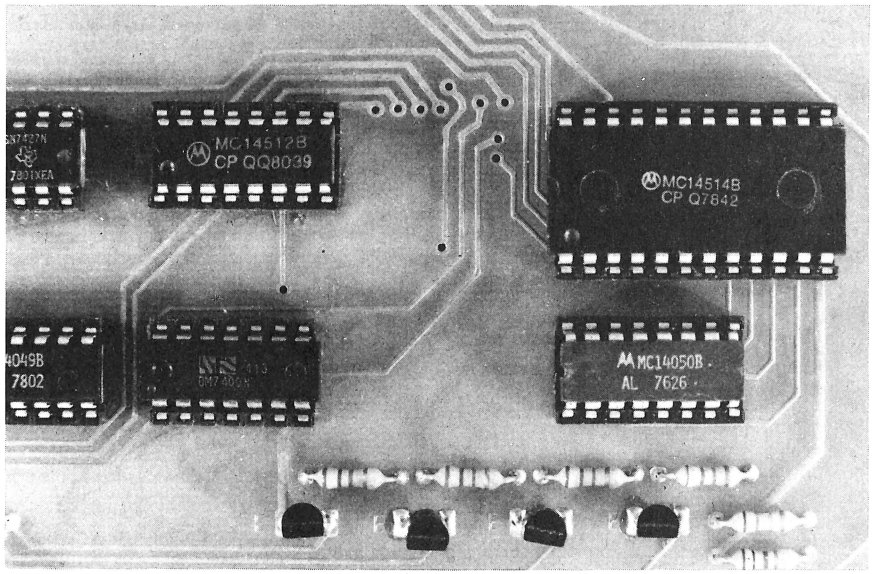
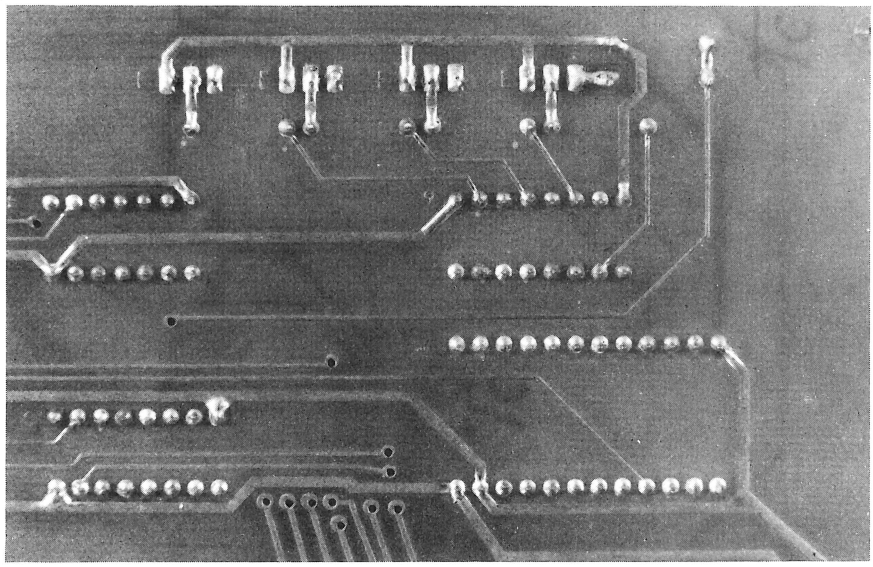


FIGURE A.1a Example of custom circuit board construction, front view.

portional to the complexity of the circuit design. Disadvantages include waiting about four weeks for the boards to be fabricated, the cost of fabrication, and the loss of modification flexibility. Advantages include decreased construction time for each circuit, increased reliability of operation, and an obviously professional appearance. Figures A.1a and A.1b show examples of this type of construction.

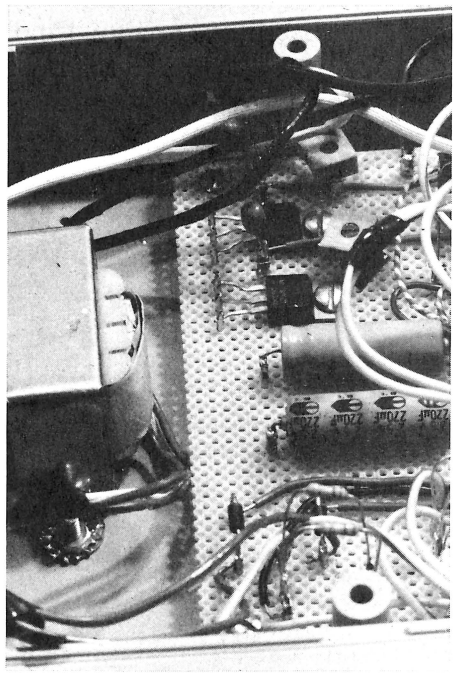
FIGURE A.1b Example of circuit board construction, rear view.



If you need to construct a single circuit that is very simple, I would recommend Vector board and push-in, solderable terminal type construction. Figure A.2 shows an example of this type of construction. Vector board (Vector Electronics Company, Inc., Sylmar, California 91342), Vector pins, and a tool to insert the pins can be purchased at your local electronics store. It is the least expensive method of construction and I have used it with success. However, this type of construction sometimes results in undesirable oscillations caused by output signal wires being in close proximity with input signal wires. Another possible problem is the introduction of high frequency noise, generated by the digital circuitry, into power supply lines. I would discourage its use with DIP packaged integrated circuits unless you are quite proficient with a soldering iron.

If you are adventurous, and have an abundance of time, you should consider laying out the foil pattern and then etching your own circuit boards (*Circuit Board Etching,* M. W. Houser, Davis Publications, New York, New York 10017, January 1981). This

FIGURE A.2 Example of Vector board construction.

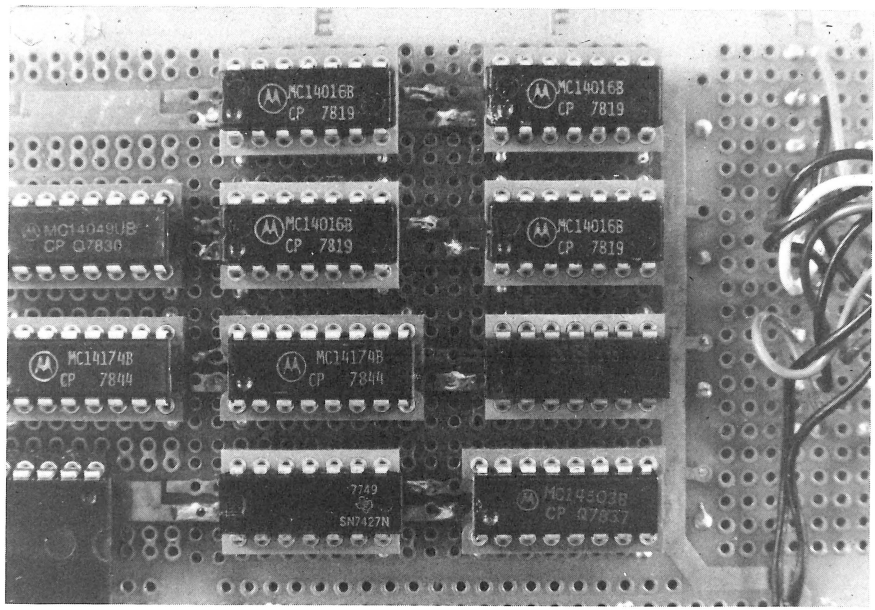


process is limited to relatively simple circuits, but the finished boards are inexpensive to produce and will result in a circuit having mechanical properties which are superior to hand-wired boards.

If the circuit is complex or if you are planning on doing several construction projects over a period of time, I would recommend that you develop your capability to produce wire-wrapped circuits (*Wire-Wrapping Techniques,* W. Sikonowiz, Davis Publications, New York, New York 10017, January 1981). This type of construction is fast and economical, and it results in circuits that will perform reliably in a variety of applications. Figures A.3a and A.3b show examples of this method of construction. Wire-wrapping allows the builder to use point-to-point construction techniques and still obtain a circuit board which is rugged enough to be put into practical use. Construction proceeds relatively fast and corrections can be easily made. While there is an initial investment, the individual cost of a finished board is comparable to other techniques.

Putting your finished circuit into a cabinet adds a great deal to the personal satisfaction that you will receive from completing

FIGURE A.3a Example of wire-wrap construction, front view.



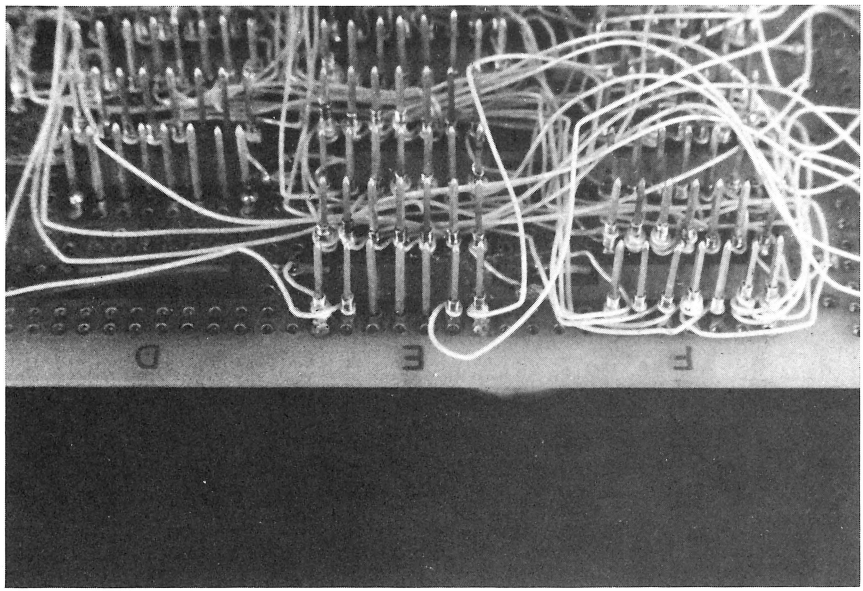
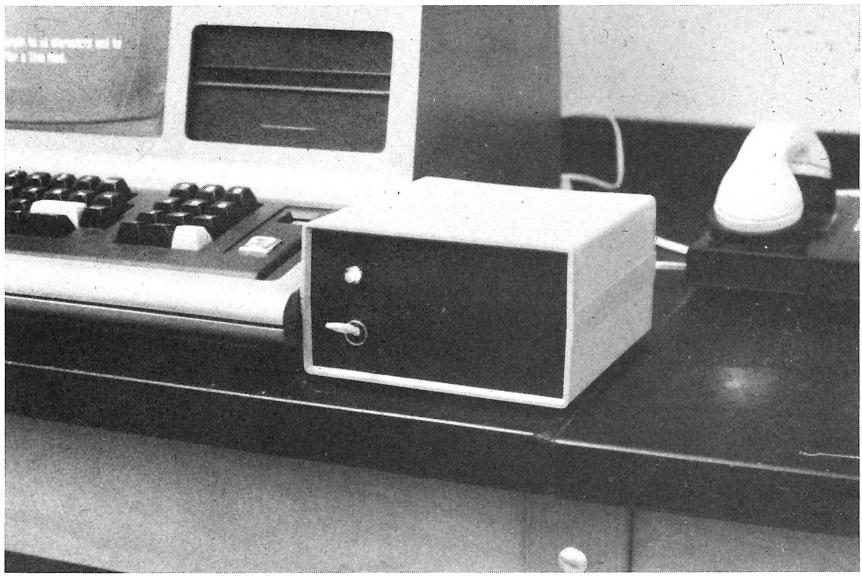


FIGURE A.3b Example of wire-wrap construction, rear view.

the project. Plastic boxes are very easy to work with and are quite adequate for the types of projects that I will be describing. Figures A.4a and A.4b show examples of this type of finished construction.

FIGURE A.4a Example of finished product.



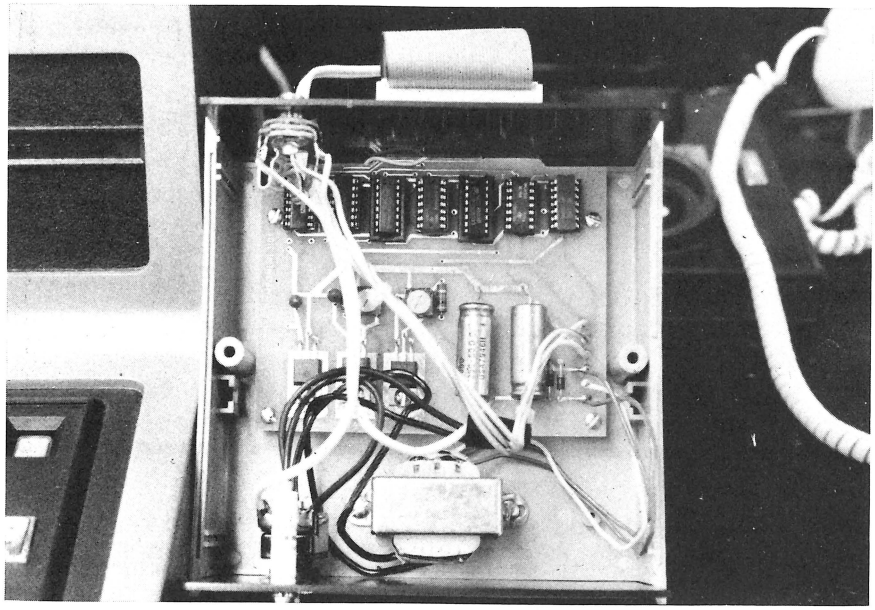


FIGURE A.4b Example of finished product.

APPENDIX B: OPERATIONAL AMPLIFIER THEORY

The operational amplifier (op amp) will be one of the most important tools you will have at your disposal when it comes time to interface some type of transducer to an A/D converter. Since most operational amplifiers have one output and two input ports, we can consider them to be a general three-port device. Their basic function is to amplify the difference between the two signals which are applied to the input ports. The amplified difference then appears at the output port. The relationship between the output voltage and the input voltages is dependent on the sign and magnitude of feedback which is supplied by the output to one or more of the inputs. As a result of feedback, we can configure our circuit to add, subtract, multiply, integrate, differentiate, compare, rectify, filter, and perform current-voltage conversion.

There are three general characteristics of the operational amplifier that make it a useful tool:

1. It has very high gain from either of the two input ports to the output port.
2. The input impedance at each input port is very high and the output impedance is very low.
3. It has very low gain when the same signal is applied to both input ports at once. Consequently, the amplifier is most sensitive to the voltage difference between the two inputs rather than the voltage difference between either input and ground. This allows the amplifier circuit to disregard many signals which would be classified as noise and to respond only to the signal coming from the transducer.

Since many of our projects deal with small magnitude signals, we will need to provide amplification, and possibly filtering, to increase our ability to resolve and accurately display these signals. The operational amplifier will allow us to combine a fifty-cent integrated circuit with a knowledge of Ohm's law, and become proficient at designing small signal amplifiers for our interface projects.

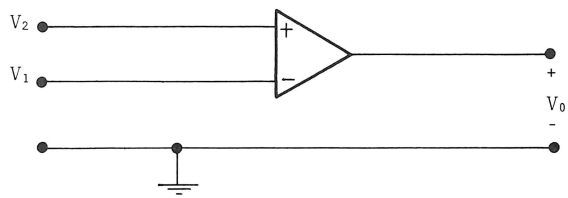


FIGURE B.1 Op-amp circuit symbol. A voltage at V_1, the inverting input, is greatly amplified and inverted to yield an out-of-phase output at V_0. A voltage at V_2, the noninverting input, is greatly amplified to yield an in-phase output at V_0.

Figure B.1 shows the operational amplifier circuit symbol. You should notice the two input terminals and the single output terminal. One of the input terminals has a negative sign associated with it (the inverting input) and one of the inputs has a positive sign associated with it (the noninverting input). There are two basic rules which we will be using to design and analyze op amp circuits:

1. When the op amp is operating in a linear region, the two input terminals are at the same voltage.
2. There can be no flow of current into either of the input terminals.

Armed with these two constraints we can begin our discussion of specific amplifier circuits.

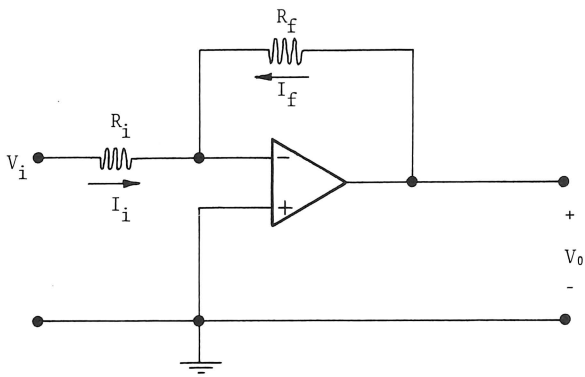
INVERTING AMPLIFIER

Figure B.2 shows a basic inverter circuit which is widely used for instrumentation purposes. The input impedence for this configuration is approximately equal to the magnitude of resistor R_i. Note that a portion of the output signal is fed back through resistor R_f to the negative input of the op amp. Reviewing the two rules which we have previously discussed, we know that both the positive and the negative inputs are at the same potential, which for this circuit is equal to 0 volts. We also know that the current flowing into or out of each of the two input terminals has to be equal to 0. Using Kirchhoff's current law we can write the following equation:

$$I_i + I_f = 0 \qquad \text{(B.2a)}$$

FIGURE B.2 Simple resistive inverting amplifier. A voltage at V_i, the inverting input, produces a voltage at the output, V_o, which is a function of the values R_i and R_f.

$$V_o = -\left[\frac{R_f}{R_i}\right] V_i$$



Using Ohm's law we can write the following two equations:

$$V_i - R_i I_i = 0 \qquad \text{(B.2b)}$$

$$V_o - R_f I_f = 0 \qquad \text{(B.2c)}$$

Solving equation B2.2b for I_i, solving equation B2.3a for I_f, and then substituting these two values back into equation B2.2a, we obtain equation B.2d:

$$(V_i/R_i) + (V_o/R_f) = 0 \qquad \text{(B.2d)}$$

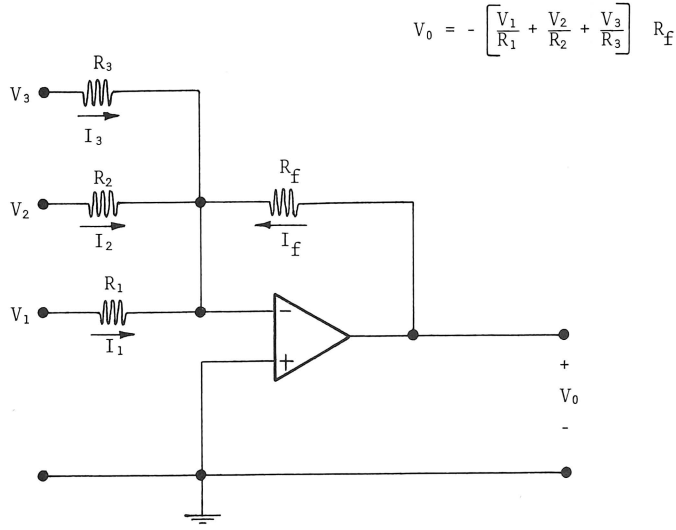
The voltage gain (K) for the circuit can then be written as follows:

$$K = V_o/V_i = -(R_f/R_i) \qquad \text{(B.2e)}$$

Figure B.3 shows a modification to the basic inverter circuit which allows us to add several input voltages together. Remembering our two basic rules, we know that the inverting and the noninverting input terminals are at the same potential and that there can be no current flowing into or out of either of these terminals. Summing currents at the inverting terminal we obtain the following equation:

$$I_1 + I_2 + I_3 + I_f = 0 \qquad \text{(B.3a)}$$

FIGURE B.3 Simple resistive inverting summing amplifier.



Using Ohm's law we can write equations for these currents in terms of the input and output voltages.

$$I_1 = V_1/R_1 \quad \text{(B.3b)}$$

$$I_2 = V_2/R_2 \quad \text{(B.3c)}$$

$$I_3 = V_3/R_3 \quad \text{(B.3d)}$$

$$I_f = V_o/R_f \quad \text{(B.3e)}$$

Substituting these equations back into equation B.3a we get equation B.3f:

$$(V_1/R_1)+(V_2/R_2)+(V_3/R_3)+(V_0/R_f)=0 \quad \text{(B.3f)}$$

Solving for the output voltage, expressed as a function of the input voltages and the resistance values, we get the following equation:

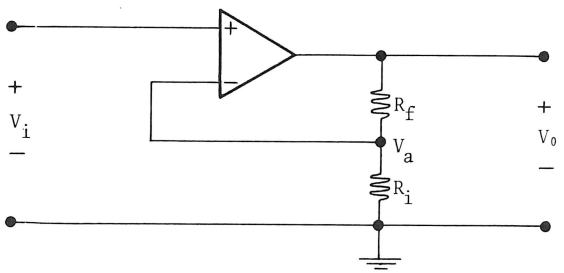
$$+V_o=(R_f/R_1)V_1+(R_f/R_2)V_2+(R_f/R_3)V_3 \quad \text{(B.3g)}$$

NONINVERTING AMPLIFIER

Figure B.4 shows an amplifier configuration which is sometimes called a *voltage follower* because the output voltage is the same polarity as the input voltage. This circuit is useful because the

FIGURE B.4 Simple resistive noninverting amplifier. A voltage at V_i, the noninverting input, produces at the output V_o, which is a function of the values R_i and R_f.

$$V_0 = \left[1 + \frac{R_f}{R_i}\right] V_i$$



input impedance is extremely large; therefore, the circuit does not draw much current from the circuit that is attached to its input. Again we have a circuit that has a portion of the output signal fed back to the inverting input through the feedback resistor R_f. The two rules which we have discussed state that the voltage at the inverting input will be equal to the voltage at the noninverting input, and that there will be no current flow into or out of either input terminal. Using Ohm's law we can write an expression which will relate the magnitude of the voltage at point a to the output voltage Vo.

$$V_a = V_o R_i/(R_i + R_f) \qquad \text{(B.4a)}$$

We know that $V_a = V_i$, and if we substitute this back into equation B.4b we get the following equation:

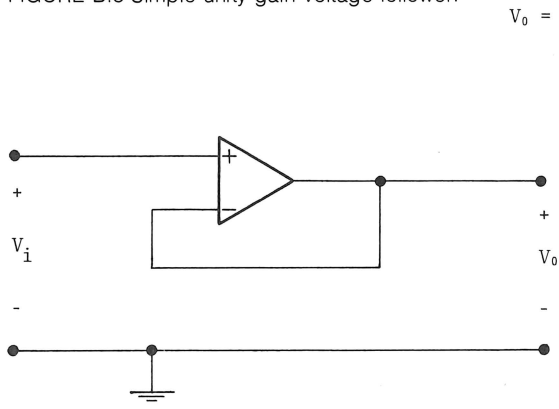
$$V_i = V_o R_i/(R_i + R_f) \qquad \text{(B.4b)}$$

By rearranging this equation we can obtain an expression which gives the voltage gain of the circuit as a function of the resistors R_i and R_f.

$$K = V_o/V_i = 1 + R_f/R_i \qquad \text{(B.4c)}$$

By looking at equation B.4c, you should be able to predict what happens to the voltage gain as a resistor R_i becomes very large. Figure B.5 shows a circuit diagram where this resistance has been

FIGURE B.5 Simple unity gain voltage follower.



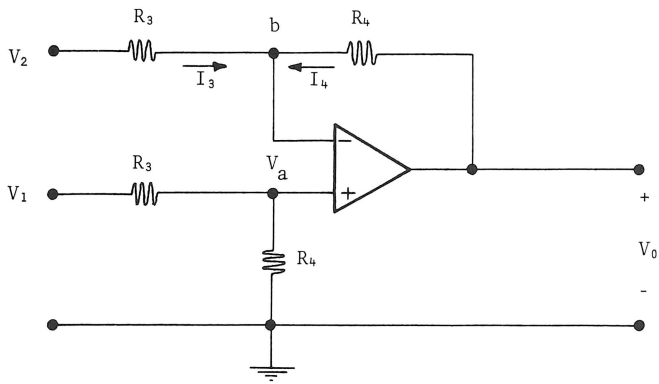
set equal to infinity (open circuit). This is a special circuit called the unity-gain voltage follower. Remembering that the voltages at the two input terminals have to be equal to one another, we can see that the output voltage is forced to be equal to the input voltage. This circuit is often used to provide impadence transformation from very high at the input to very low at the output.

DIFFERENTIAL AMPLIFIER

We found that we could add two or more signals together by using the inverting summing amplifier configuration. We will now take a look at a circuit which will allow us to subtract one signal from another. Figure B.6 shows an operational amplifier used as a differential amplifier. One of the advantages to using this circuit is that the circuit subtracts voltages applied to both inputs therefore producing an output only when the input voltages are not equal. This is useful when we have a balanced input circuit and need to reduce noise which is common to both of the inputs. Remembering that the voltage at the inverting input has to equal the voltage at the noninverting input and that no current can flow into or out of either terminal, and using Ohm's law, we can write

FIGURE B.6 Simple resistive differential amplifier. This circuit is configured so that the output voltage, V_0, is equal to the difference of the input voltages, V_1 and V_2, multiplied by a constant which is a function of the resistors R_3 and R_4.

$$V_0 = \frac{R_4}{R_3}\left[V_1 - V_2\right]$$



an equation for the voltage at point a in terms of the input voltage V_1:

$$V_a = V_1 R_4/(R_3 + R_4) \quad \text{(B.6a)}$$

This voltage has to be equal to the voltage at point b. We also know that the following relationship exists between current I_3 and current I_4:

$$I_3 + I_4 = 0 \quad \text{(B.6b)}$$

We can write the following equations to relate the output voltage to the input voltages:

$$I_3 = (V_2 - V_b)/R_3 \quad \text{(B.6c)}$$

$$I_4 = (V_o - V_b)/R_4 \quad \text{(B.6d)}$$

Substituting equation B.6a into equations B.6c and B.6d and then substituting these equations back into equation B.6b gives the following result:

$$V_o/R_4 = (V_1 - V_2)(1/R_3) \quad \text{(B.6e)}$$

Rearranging this equation gives us an equation which relates the output voltage to the input voltages as a function of the resistance values.

$$V_o = (R_4/R_3)(V_1 - V_2) \quad \text{(B.6f)}$$

INTEGRATING AMPLIFIER

The integrating amplifier (see Figure B.7) is a circuit whose gain varies as a function of frequency making it different from the circuits we have previously considered. Detailed analysis would show that the output voltage will be related to the magnitude and the frequency of the input voltage by the following equation:

$$V_o/V_i = -1/(wRC) \quad \text{(B.7a)}$$

$$V_0 = -\frac{1}{RC}\int_{t_i}^{t_2} V_i \, dt$$

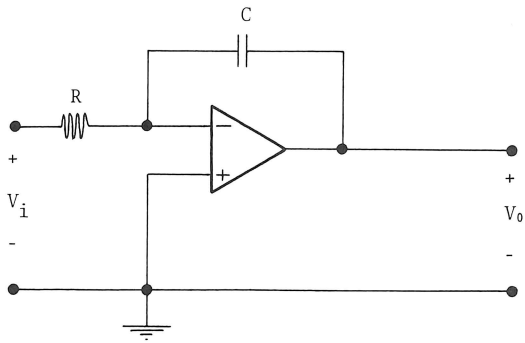


FIGURE B.7 Simple integrating amplifier. The time constant of this circuit is directly related to the product of resistor R and capacitor C.

This equation can also be written as a function of time; this may actually be a more familiar representation for the majority of readers:

$$V_o = -1/RC \int_{t_i}^{t_2} V_i \, d_t \qquad \text{(B.7b)}$$

Figure B.8 shows an integrator which has had a resistor added in parallel with the capacitor. This provides us with a circuit, called a *low pass filter*, which is useful for attenuating high frequency noise. As with the integrator, the frequency response is given by the ratio of feedback to input impedance. However, at low frequencies the circuit behaves like an inverter because the impedance of capacitor C is large when compared to the resistor R_2. At higher frequencies, the circuit behaves like an integrator because the impedance of C becomes smaller than R_2. Equation B.8a expresses the gain of this circuit as a function of frequency:

$$V_o/V_i = (R_2/R_1)(w/R_2C)(1/1+ w/R_2C) \qquad \text{(B.8a)}$$

At low frequencies this equation reduces to the following equation which will be recognized as the equation for the simple inverting amplifier:

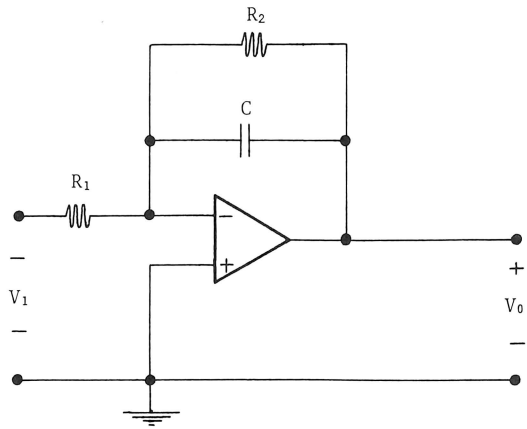


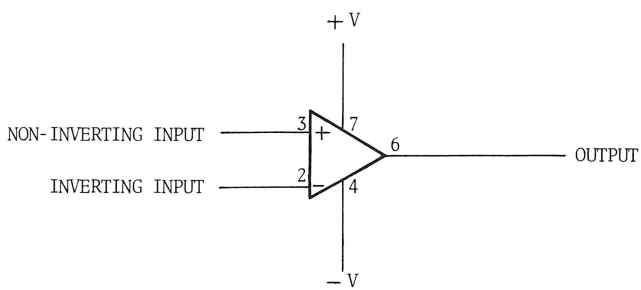
FIGURE B.8 Simple low-pass filter. The low frequency gain of the circuit is a function of R_1 and R_2. The 3_{db} corner frequency is determined by the values of capacitor C and resistor R_2.

$$V_o/V_i = -(R_f/R_i) \qquad \text{(B.8b)}$$

At high frequencies equation B.8a will reduce to equation B.7a. When a circuit designer needs to limit the frequency response of a wide-band amplifier, there is no need to add a separate stage but only to add the correct size capacitor to the existing circuit.

There are many operational amplifiers which you could use in the circuits which we have discussed. An op-amp which is commonly available, low in cost, and easy to use is the 741. This is a general purpose device which provides output short circuit protection, internal phase compensation, and latch free operation. Another device which is readily available is the CA3140. This operational amplifier differs from the 741 by having MOS/FET input stages which provide high input impedance. The pin configuration for both of these devices is shown in Figure B.9.

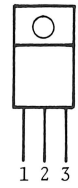
FIGURE B.9 Pin assignment for the 741 and CA3140T operational amplifiers.



APPENDIX C: POWER SUPPLIES

The widespread availability of three terminal regulators makes the design and construction of power supplies for digital and analog circuits almost a simple task. In the past, power supplies were generally made from a number of discrete components. Today, advancements in fabrication techniques related to monolithic semiconductors have enabled a number of discrete components to be incorporated into a single chip. This has resulted in a series of low-cost positive and negative regulators which are extremely easy to use, and difficult to abuse. Monolithic voltage regulators usually have a series pass transistor power control element, a reference source, and current overload protection all on the same chip. As a result of this, no adjustments are required to set up the output voltage, and it is virtually impossible to destroy the regulator.

Figure C.1 shows a schematic of a + 5 volt power supply that can provide up to .5 amperes of current with adequate heatsinking.



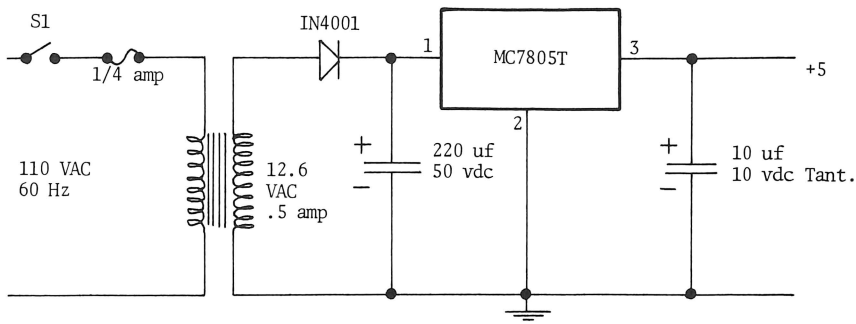


FIGURE C.1 Positive 5-volt power supply.

Figure C.2 shows a schematic of a +12 and −12 power supply that can provide up to .5 amperes of current with adequate heatsinking.

Once you have constructed either of the supplies, you should check to make sure that the output voltage is what you were expecting it to be. You should be concerned about the following:

1. Treat the 110-volt line voltage with care.
2. Make sure that the polarity of the filter capacitators is correct.
3. Make sure that the polarity of the diodes is correct.
4. The positive and negative regulators do not use the same pin configuration. Be sure that you have used the correct pins for input, output, and ground.

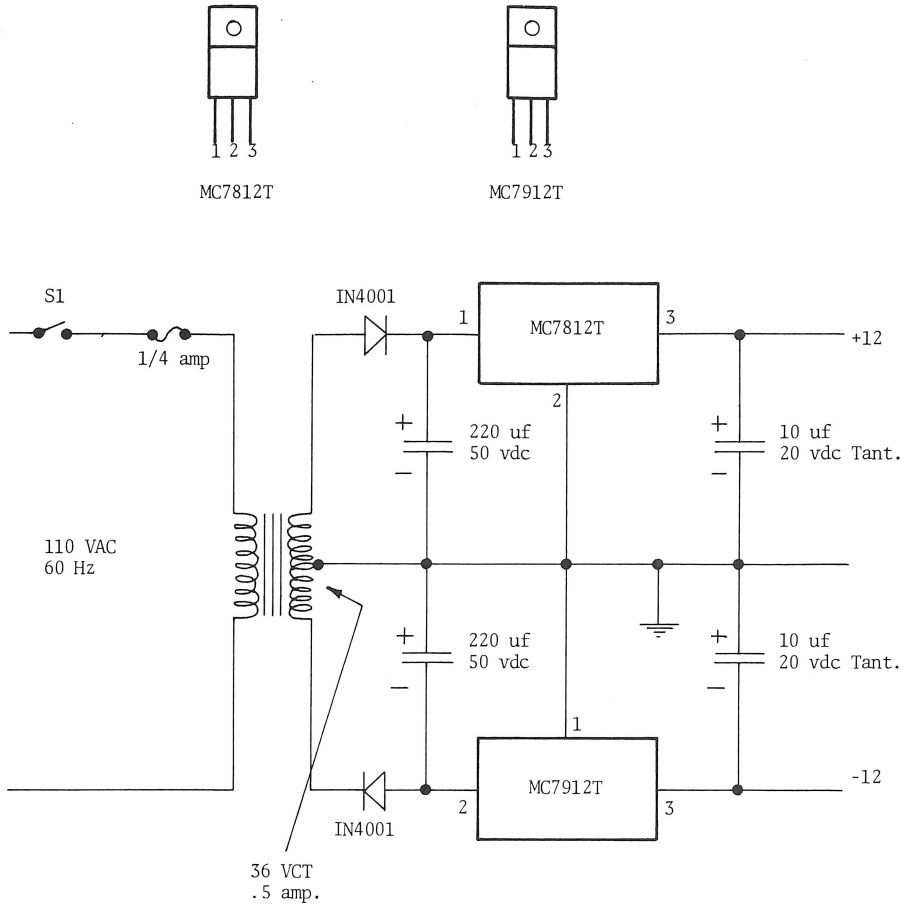


FIGURE C.2 Positive 12, negative 12 volt power supply.

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